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Final Report

INVESTIGATION OF DIRECT SOLAR-TO-MICROWAVE ENERGY CONVERSION TECHNIQUES

(NASA-CR-161883) INVESTIGATION OF DIRECT
SOLAR-TO-MICROWAVE ENERGY CONVERSION
TECHNIQUES Final Report (Teledyne Brown
Engineering) 107 p HC A06/MF A01 CSCL 10A

N82-11544

G3/44 01066
Unclass

January 1978



 **TELEDYNE
BROWN ENGINEERING**

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FINAL REPORT
ESD78-MSFC-2174

INVESTIGATION OF DIRECT SOLAR-TO-MICROWAVE
ENERGY CONVERSION TECHNIQUES

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January 1978

Prepared For

PROGRAM DEVELOPMENT OFFICE
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ABSTRACT

This effort was undertaken to identify alternative methods of producing microwave energy from solar radiation for purposes of directing power to the Earth from space. Specifically, methods of conversion of optical radiation into microwave radiation by the most direct means were investigated. Approaches based on demonstrated device functioning and basic phenomenologies were developed. No system concept was developed that is competitive with current baseline concepts. The most direct methods of conversion appear to require an initial step of production of coherent laser radiation. Other methods generally require production of electron streams for use in solid-state or cavity-oscillator systems. Further development is suggested to be worthwhile for suggested devices and on concepts utilizing a free-electron stream for the intra-space station power transport mechanism.

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1. INTRODUCTION

Space-based solar power systems have been conceived of as being a potentially viable economic source of electrical power on Earth. The basic system concept was originated by Dr. P. F. Glaser in 1968 and reported on extensively in 1974 (Ref. 1). Figure 1-1 depicts the elements of the system. Solar-oriented photovoltaic cell arrays are structured surrounding an Earth-oriented microwave generation and radiating system. Variations to this concept include the use of a thermal conversion and a Rankine-cycle engine to drive electric generators to supply power to the microwave generators. Figure 1-2 shows the Rockwell International concept for this system and a comparable Boeing concept (Refs. 2 and 3). These concepts involve concentration of solar radiation onto a boiler system, which in turn produces steam (or other suitable working fluid) to drive turbogenerators. Another alternative to photovoltaic cell power conversion is the Boeing concept of using thermionic diodes. This concept also involves use of solar radiation concentrators to increase the incident power density on the diodes (Ref. 3).

These and other alternative concepts generally involve a process as shown in Figure 1-3. The salient features of this grouping of concepts for purposes of this study are contained in the optical-electrical energy converter and microwave generator subsystems. All of the concepts discussed, as well as others not mentioned above, involve the production of electrical power transmitted through solid conductors as either direct current or low-frequency alternating current. Either a klystron or amplatron microwave generator system is then employed to convert this energy into transmittable energy. A typical process flow for these systems is shown in Figure 1-4.

This study was initiated to study the possibilities of more directly converting solar irradiance on a collector system into microwave energy which can be transmitted to the ground. Figure 1-5 shows the outputs that have resulted and which are discussed in this report.

- CONCENTRATION RATIO = 1
- OVERALL EFFICIENCY = 6.0%
- 11.3 kg/kW

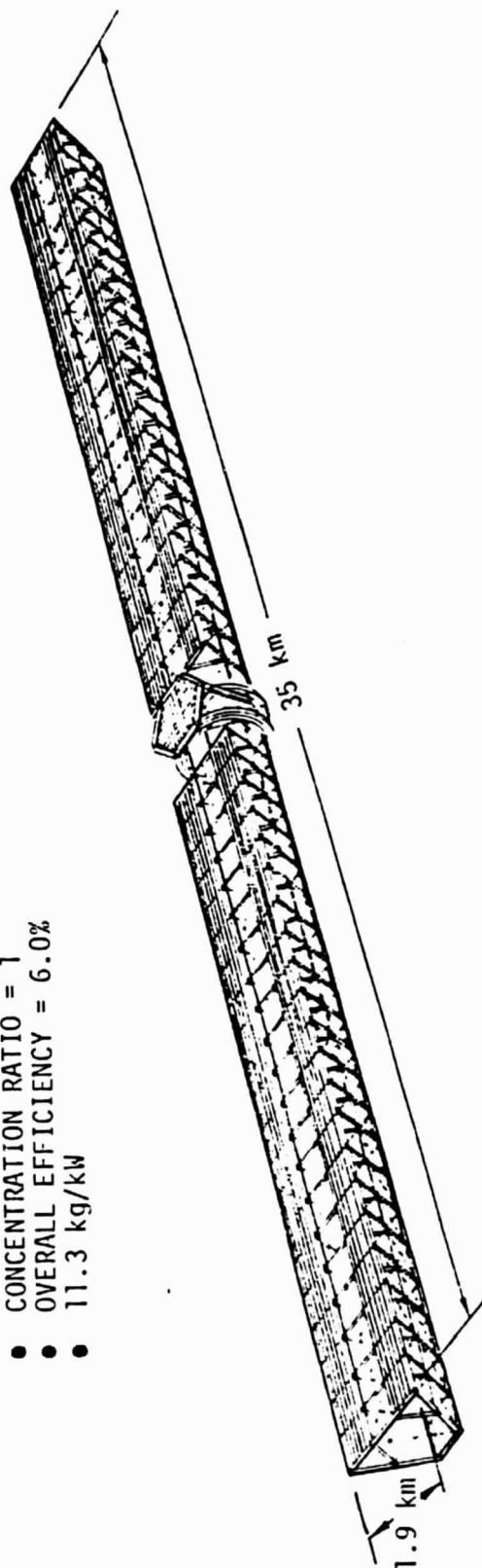
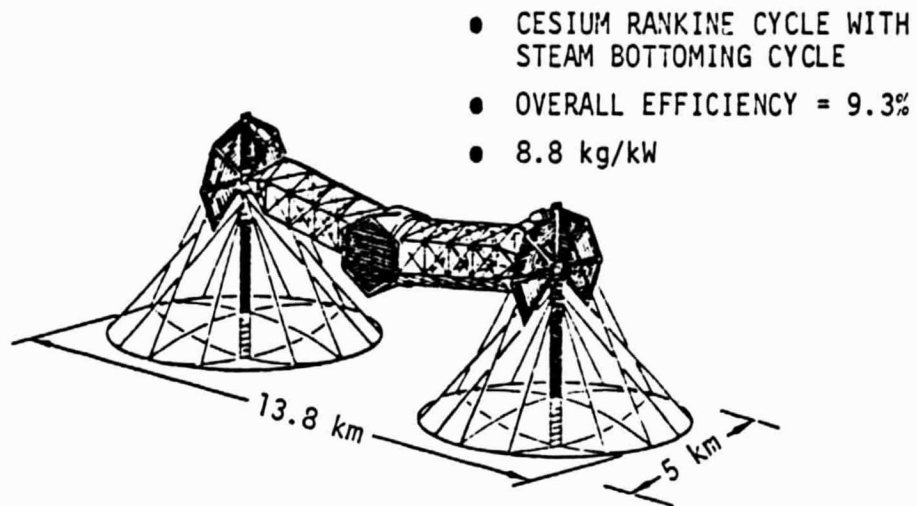
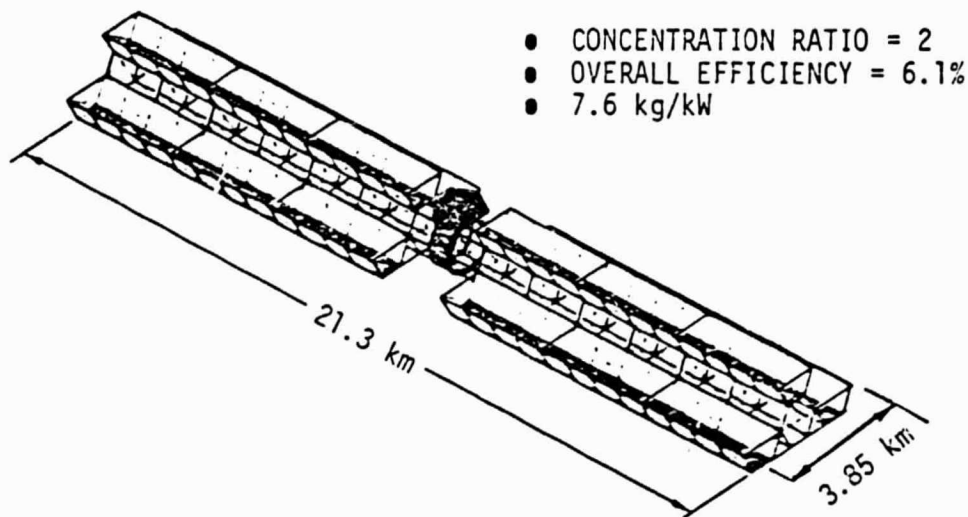


FIGURE 1-1. BASELINE SYSTEM SILICON PHOTOVOLTAIC CONVERSION PRODUCING
5 GW AT UTILITY INTERFACES

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SOLAR THERMAL



GaAs PHOTOVOLTAIC

FIGURE 1-2. BASELINE SYSTEMS: ALTERNATIVES - EACH PRODUCES 5 GW UTILITY INTERFACE

During the course of the study, a series of tasks were performed to generate the data. These tasks were as shown in Figure 1-6.

For purposes of presentation, the material has been organized in a different sequence. In the next section, a brief discussion is presented of what the general requirements on direct energy conversion systems might be. During the study, the technical areas of investigation have generally been segregated into energy transportation techniques and microwave generation techniques. These types are covered in sequence. The total system concepts that might be developed are then synthesized, and an outline of a technology developed plan is given. References to the material presented are collected at the conclusion of each of the discussions. In addition, a more extensive bibliography has been collected and completes this report.

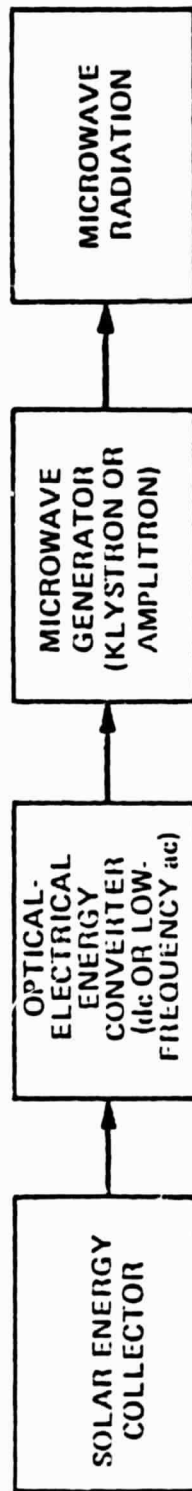


FIGURE 1-3. BASELINE SYSTEMS: SCHEMATIC REPRESENTATION

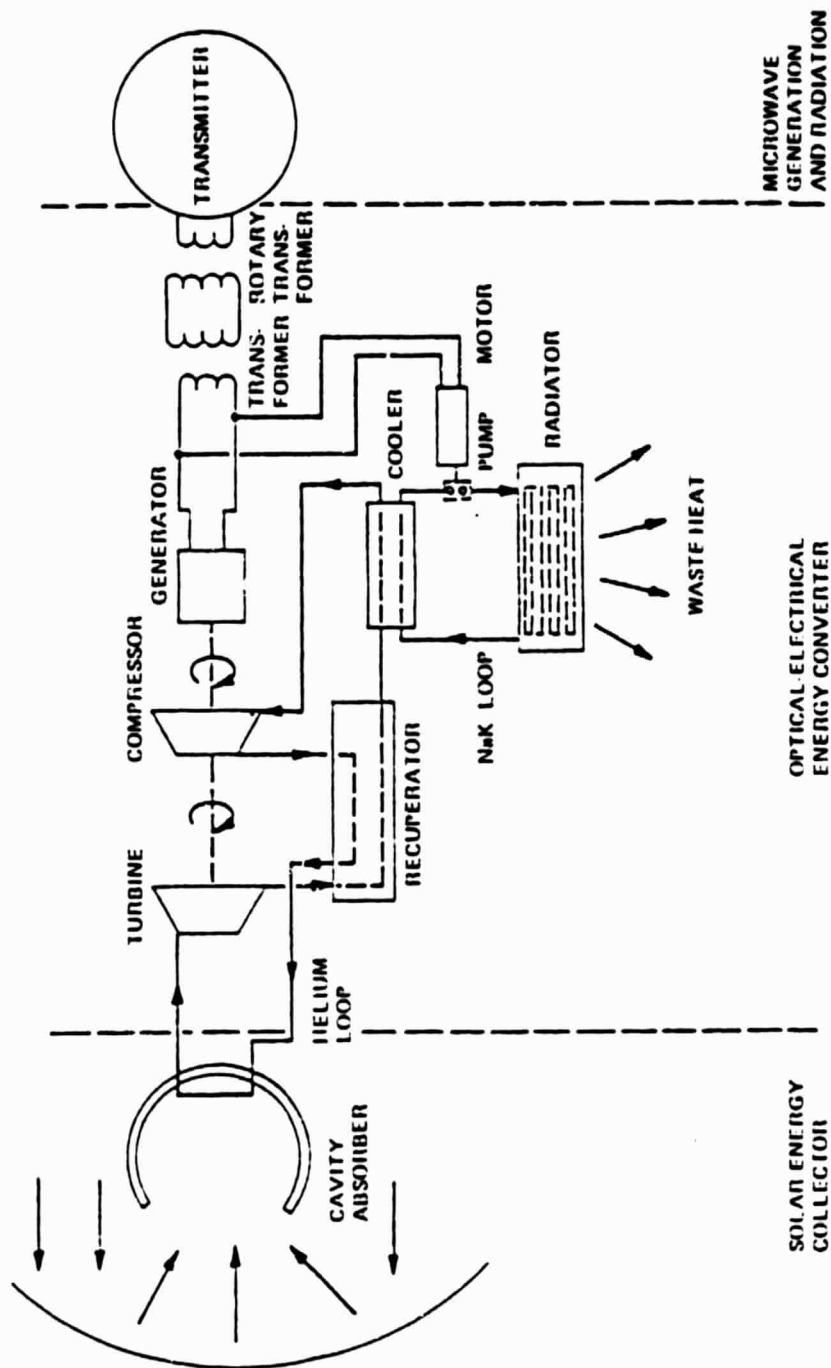


FIGURE 1-4. BASELINE SYSTEM: TYPICAL PROCESS FLOW (SOLAR BRAYTON CYCLE)

- IDENTIFICATION OF CONVERSION MECHANISMS
- SPECIFICATION OF RESEARCH REQUIREMENTS FOR SELECTED TECHNIQUES
- CONCEPTS FOR UTILIZATION OF TECHNIQUE FOR AN ORBITING POWER STATION
- IDENTIFICATION OF LOCATION OF RESEARCH GROUPS WORKING ON SELECTED TECHNIQUES
- APPROACH TO DEVELOPMENT OF TECHNOLOGY TO DETERMINE FEASIBILITY OF POTENTIALLY USEFUL CONCEPTS

FIGURE 1-5. OUTPUTS FROM PROJECT

- TASK I - LITERATURE SEARCH FOR MICROWAVE PRODUCTION MECHANISMS
- TASK II - COLLECTION OF MATERIALS AND PHYSICAL PROPERTIES RELEVANT TO PRODUCTION OF MICROWAVE ENERGY WITHIN THE SPECIFIED FREQUENCY RANGE OF 2.45 to 5 GHz. THE PURPOSE OF THIS TASK IS TO IDENTIFY MATERIALS THAT MIGHT BE USED TO PRODUCE DEVICES OPERATING BY KNOWN PRINCIPLES AT THE SELECTED FREQUENCY OR TO ACT AS AUXILIARY DEVICES FOR SUCH FUNCTIONS.
- TASK III - IDENTIFICATION OF MATERIALS AND TECHNIQUES OF MICROWAVE GENERATION WHERE DIRECT OPTICAL PUMPING IS POSSIBLE
- TASK IV - INVESTIGATION OF THE PRACTICAL REALIZATION OF AN OPTICALLY PUMPED MASER
- TASK V - SELECTION OF DEVICES OR PHENOMENA THAT COULD RESULT IN DEVICES THAT COULD BE USED FOR THIS APPLICATION. INVESTIGATION OF EFFICIENCY, CONVERSION TECHNIQUES, AND TECHNOLOGY DEVELOPMENT THAT IS REQUIRED.
- TASK VI - SPECIFICATION OF A DEVELOPMENT PROGRAM TO FURTHER INVESTIGATE PROMISING TECHNIQUES.

FIGURE 1-6. TASKS PERFORMED TO CONDUCT THE STUDY

2. SYSTEM REQUIREMENTS

The requirements for alternative systems must be specified according to the guidelines shown in Figure 2-1. The baselined system serve as the basis for information on functional relationships.

The constraints and requirements based on physical relationships were as shown in Figure 2-2. The study was constrained to investigate methods of conversion of solar energy to microwave energy in the 2- to 5-GHz region of the spectrum. Although efficiency of the processes investigated was not to be a primary consideration, we found it necessary to investigate conversion efficiencies to place realistic estimates on how practical a particular technique might be. The Earth-based receiving station characteristics were not considered and were assumed to be a constraint on the system. Because the investigation was to consider techniques beyond the state of the art, research into possible techniques extended to investigation of fundamental processes which might be applied as well as identification of devices.

In the Introduction, attention was called to the fact that a single-step process was not a feasible concept; in order to be comprehensive, energy conversion and generation processes which covered the parameters shown in Figure 2-3 must be considered.

Therefore, direct conversion of collected solar energy into microwave energy must still be thought of as a stepwise process. For orbiting power stations which are to collect solar radiation and transmit it to the ground somewhere in the frequency band of 2 to 5 GHz, the conversion relationships are as shown in Table 2-1 (Ref. 4).

The scope of this study could not cover the total system constraints imposed by the space environment. Some of these constraints have been investigated during definition of the baseline systems concepts and others will not be important for consideration until initial designs begin. Probably the most important environmental characteristics of space to this study are the radiation content, the magnetic field,

and the local plasma content. The interactions of these properties with energy conversion and microwave generation devices can be significant. In general, these interactions were not considered at this time.

Several potentially useful fundamental processes involve mechanisms occurring in plasmas. Characteristic number densities and temperature for the magnetosphere, the ionosphere, and a fusion machine plasma are presented in Figure 2-4. In order to have energy densities high enough for practical systems, plasma densities considerably higher than ambient densities would appear necessary. This requirement translates to the need for containment of any plasma system considered.

- BASELINED SYSTEM
- CONSTRAINTS AND PHYSICAL INTERRELATIONSHIPS
- CONVERSION PARAMETERS OF INTEREST

FIGURE 2-1. SYSTEM REQUIREMENTS

CONSTRAINTS

- MICROWAVE OUTPUT
- EFFICIENCY OF PROCESS NOT INITIAL CONSIDERATION
- GROUND RECEIVING SYSTEM REMAINS THE SAME

REQUIREMENTS BASED ON PHYSICAL INTERRELATIONSHIPS

- INVESTIGATE FUNDAMENTAL PROCESSES
- EXAMINE DEVICE TECHNOLOGY
- CONSIDER OPERATION IN SPACE ENVIRONMENT

FIGURE 2-2. CONSTRAINTS AND PHYSICAL INTERRELATIONSHIPS

- OPTICAL RADIATION - OPTICAL RADIATION
 - THERMAL ENERGY
 - ELECTRONIC ENERGY
 - MECHANICAL ENERGY

FIGURE 2-3. CONVERSION PARAMETERS OF INTEREST

TABLE 2-1. ENERGY CONVERSION PARAMETERS

SOLAR IRRADIANCE AT 1 AU		1,400 W/m ²	
	WAVELENGTH RANGE	FREQUENCY RANGE (Hz)	PHOTON ENERGY (eV)
SOLAR IRRADIANCE	0.3 TO 0.78 μm ^(a)	3.8×10^{14} - 10×10^{14}	4.1 TO 1.6
MICROWAVE GENERATION	0.15 TO 0.6 m ^(b)	2×10^9 - 5×10^9	— ^(c)

(a) WAVELENGTH RANGE WITHIN WHICH 98% OF RADIATION LIES

(b) WAVELENGTH RANGE WITHIN WHICH EMITTED RADIATION MUST LIE

(c) NOT RELEVANT

<u>PLASMA</u>	<u>N (cm⁻³)</u>	<u>T (K)</u>
MAGNETOSPHERE	1	(5 keV)
IONOSPHERE	10 ⁶	10 ³
Q-PLASMA	10 ⁸	10 ⁵

FIGURE 2-4. TYPICAL PLASMA DENSITIES

REFERENCES - SECTIONS 1 AND 2

1. P. F. Glaser, O. E. Maynard, J. Mackovciak, Jr., and E. L. Ralph, "Feasibility Study of a Satellite Solar Power Station", NASA CR-2357, February 1974
2. "Satellite Power System Concept Definition Study - First Quarterly Review", NASA, George C. Marshall Space Flight Center, PD 77-21, June 1977
3. "Space-Based Power Conversion and Power Relay Systems: Preliminary Analyses of Alternate Systems", Boeing Aerospace Company, Contract NAS8-31628, Second Performance Review, January 1976
4. S. L. Valley, ed., "Handbook of Geophysical and Space Environments", U.S. Air Force Cambridge Research Laboratories, 1965

3. ENERGY TRANSFORMATION TECHNIQUES

To take as an input solar radiation and to output microwave radiation, we have concluded that a series of stepwise processes is necessary. No single-step concept was identified during the course of the study. As a result of identifying several concepts for multi-step processes, the descriptions of transformation concepts have been broken out into "energy transformation techniques" and "microwave generation techniques". Figure 3-1 shows a further breakout for this section for the topics covered. Both concepts and techniques are discussed when appropriate in relation to solar radiation characteristics. Because one of the microwave generation concepts discussed in the next section requires high-energy electrons, electron accelerators are discussed as a part of this section.

The method of presentation is in the form of "fact sheets", one for each device or concept.

- SOLAR INSOLATION CHARACTERISTICS
- TRANSFORMATION CONCEPTS
- TRANSFORMATION DEVICES AND TECHNIQUES
- ACCELERATOR CONCEPTS

FIGURE 3-1. ENERGY TRANSFORMATION TECHNIQUES

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3.1 DEVICE OR PRINCIPLE: SOLAR-PUMPED LASER FOR DIFFERENCE FREQUENCY GENERATION

Description of Device or Principle: For an optically pumped laser to be a candidate for direct solar pumping, it must have both a very low oscillation threshold and absorption bands compatible with solar spectral emission. Nd:YAG and Nd:glass lasers, which operate at 1.064 μm and 1.059 μm , respectively, meet the above requirements, and solar pumping of both types has been demonstrated (Refs. 1 and 2). The pumping efficiency of Nd:YAG can be enhanced with the introduction of chromium in the laser material for the following reason. Two absorption bands in the blue and yellow region of the spectrum are effective in pumping the Cr^{3+} ion, and the energy level scheme is such that excitation transfer occurs from the Cr^{3+} to the Nd^{3+} . The location of the Cr^{3+} and Nd^{3+} absorption bands within the solar spectrum is depicted in Figure 3.1-1. It is evident from Figure 3.1-1 that the Nd:YAG laser has a good atomic quantum efficiency; i.e., a sizeable fraction of the energy of a pump photon is utilized in the laser transition.

Limitations on Device or Principle: While the placement of the absorption bands in Nd:Cr:YAG relative to the solar spectrum is excellent and while the atomic quantum efficiency is good, overall energy conversion efficiency is poor. Reference 2 reports 2.05 W TEM_{00} CW output using a 24-in.-diameter collector. By assuming an irradiance of 1 W-cm^{-2} and by making a reasonable allowance for the obscuration due to the collector secondary optics, one can estimate a collected solar power of about 2,000 W and hence an overall efficiency of about 0.1%.

Potential Method of Employment of Device or Principle in System: The output of a solar-pumped laser would, in the present context, be used to generate microwaves through a parametric interaction in a non-linear medium. To achieve a stable microwave output, one would need to operate the laser in a single-mode, frequency-stabilized condition (Figure 3.1-2).

Single-mode and hence single-frequency operation in solid ion lasers does not occur naturally because of spatial hole burning resulting from the standing wave intensity pattern established by the resonator optics and from the low rate of energy diffusion between lattice sites in the solid-state medium. Because different longitudinal modes occupy different regions in space, the gain medium will support several modes simultaneously. One can obtain single-mode operation either by introducing a frequency-selective device into the cavity or by eliminating the standing wave intensity pattern (Figure 3.1-3). Both approaches have been used successfully on Nd:YAG at low power levels (Refs. 3 through 5).

Because the frequency of oscillation is a highly sensitive function of intracavity optical path length, both mechanical vibrations and temperature fluctuations and gradients profoundly affect frequency stability. However, with proper attention to vibration isolation and by employing an active control system incorporating a frequency reference and a piezoelectric drive on one of the resonator mirrors, one can in practice achieve good frequency stability (Ref. 6).

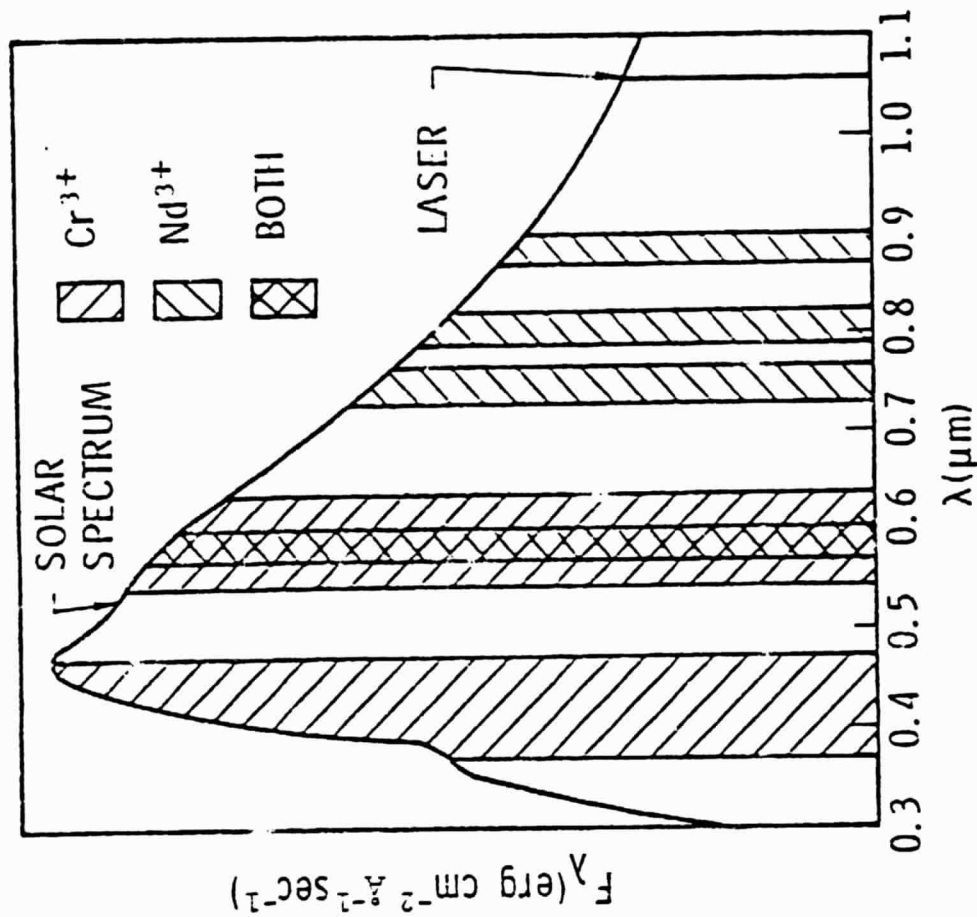
Conclusions (Figure 3.1-4): Although good progress has been made in efforts to develop and adapt to a space environment a direct-solar-pumped Nd:YAG laser for use as a satellite-borne optical communications transmitter, the difficulty of achieving stable single-frequency operation at interesting power levels and the low-energy conversion efficiency render Nd:YAG unattractive for the present purpose. Gas lasers offer advantages over solid-state lasers because material limitations are less severe, large media volumes are available, and mode selection is easier. While a number of candidates for direct solar pumping exist, it would appear that solar pumping of a gas laser has yet to be reported (Ref. 7).

References, Section 3.1:

1. C. G. Young, Applied Optics, 5, No. 6, pp. 993-997, June 1966
2. J. Falls, L. Huff, and J. D. Taynor, CLEA Paper 4.6, 1975
3. H. G. Danielmeyer, IEEE J. Quantum Electron., QE-6, pp. 101-104, February 1970
4. P. W. Smith, M. V. Schneider, and H. G. Danielmeyer, Bell Syst. Tech. J., 48, pp. 1405-1420, May 1969
5. D. A. Draegert, IEEE J. Quantum Electron., QE-8, pp. 235-239, February 1972
6. P. W. Smith, Proc. IEEE, 60, pp. 422-440, April 1972
7. R. V. Hess, A. Javan, and P. Brockman, "Proc. of Princeton U. Conf. on Partially Ionized and Uranium Plasmas", pp. 239-243, September 1976

PERFORMANCE

- COLLECTED SOLAR POWER
 - ▲ TOTAL ~400 W
 - ▲ IN 0.4- to 0.9- μ m PASSBAND ~200 W
- CW OUTPUT POWER AT 1.06 μ m
 - ▲ 5.6-W MULTIMODE
 - ▲ 2.05-W TEM₀₀ MODE
- ESTIMATE EFFICIENCY
 - ▲ 0.5% OF TOTAL COLLECTED POWER
 - ▲ 1.0% OF 0.4 TO 0.5 μ m PASSBAND
- SIZES
 - ▲ PACKAGE LESS COLLECTOR - 200 in³
 - ▲ PACKAGE WEIGHT - 10 lb
 - ▲ LASER ROD - 3 x 30 mm



ABSORPTION BANDS IN Nd³⁺:Cr³⁺:YAG

FIGURE 3.1-1. Nd:Cr:YAG SOLAR-PUMPED LASER

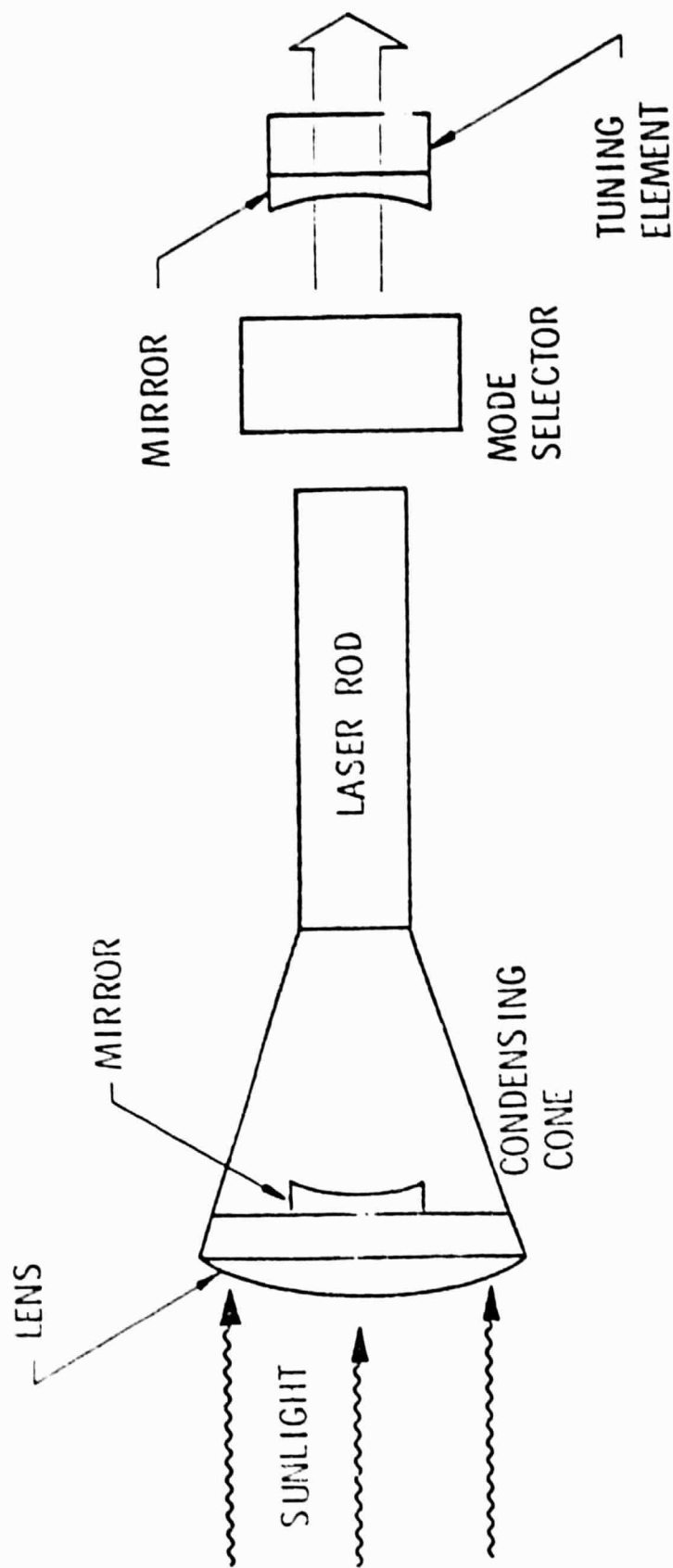
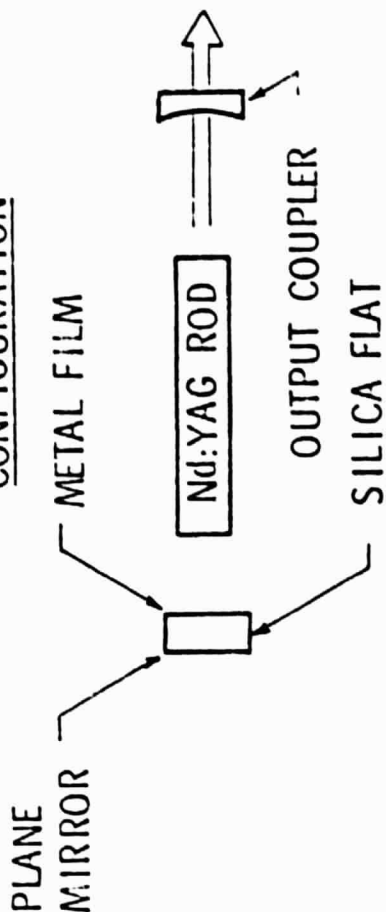


FIGURE 3.1-2. ENERGY TRANSFORMATION TECHNIQUE - SOLAR-PUMPED LASER FOR DIFFERENCE FREQUENCY GENERATION

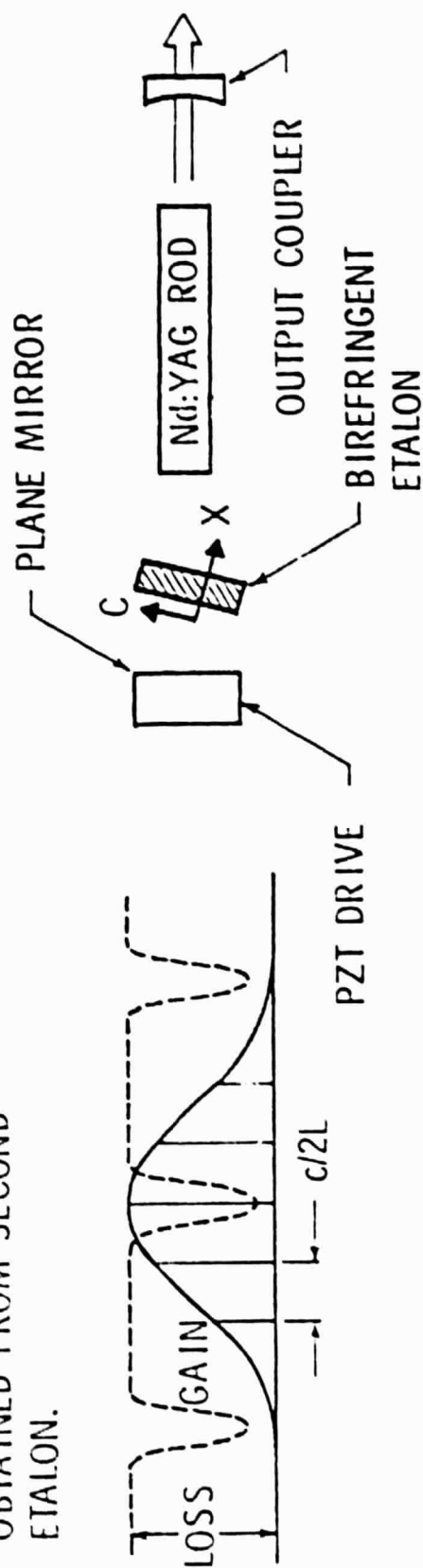
CONCEPT

- MANY MODES OF SIMPLE RESONATOR SUPPORTED BY Nd:YAG GAIN.
- INTRACAVITY ETALON CAN SUPPRESS ALL MODES BUT ONE WITHIN GAIN REGION.
- FREQUENCY DISCRIMINANT FOR STABILIZATION CAN BE OBTAINED FROM SECOND ETALON.

CONFIGURATION



MODE CONTROL



FREQUENCY AND MODE CONTROL

FIGURE 3.1-3. MODE AND FREQUENCY CONTROL

- LOCATION OF Nd:Cr:YAG ABSORPTION BANDS RELATIVE TO SOLAR EMISSION SPECTRUM IS VERY GOOD.
- ATOMIC QUANTUM EFFICIENCY OF Nd:Cr:YAG LASER IS VERY GOOD.
- DEMONSTRATED SOLAR-TO-SINGLE-MODE LASER ENERGY CONVERSION HAS LOW OVERALL EFFICIENCY.
- BOTH MODE SELECTION AND FREQUENCY STABILIZATION HAVE BEEN DEMONSTRATED IN Nd:YAG LASER.
- BROAD Nd:Cr:YAG GAIN BANDWIDTH SHOULD MAKE A 2-5 GHz DIFFERENCE FREQUENCY READILY ATTAINABLE.
- DEVELOPMENT OF A PHOTOEXCITED GAS LASER COULD AVOID MATERIAL AND GAIN VOLUME LIMITATIONS ASSOCIATED WITH CRYSTALLINE SOLID-STATE LASERS.

FIGURE 3.1-4. SOLAR-PUMPED LASER CONCLUSIONS

3.2 DEVICE OR PRINCIPLE: THERMIONIC CONVERTER

Description of Device or Principle: The physical mechanism on which a thermionic converter is based is thermionic emission. A converter is typically configured as a diode structure consisting of a heated emitter and a cooled collector whose Fermi level is more negative than that of the emitter. By connecting a load between the cathode and anode, one can obtain useful electrical power with reasonably good thermodynamic efficiency (Figure 3.2-1). Typical operating characteristics are presented in Table 3.2-1 (Ref. 1).

Thermionic converters have been configured in a variety of diode and triode forms. All of these converter forms can be classified into two broad families: vacuum converters and vapor- or gas-filled converters. The latter class can be partitioned further into low- and high-pressure types, depending on whether electron-vapor collisions can be neglected in the analysis of converter performance characteristics. Of all the various types of thermionic converters built and tested, high-pressure cesium diodes with refractory-metal electrodes have performed best (Ref. 2). The presence of cesium vapor enhances thermionic electron emission by reducing the work functions of the electrodes and improves electron transport between electrodes by reducing negative space charge.

Limitations on Device or Principle: It is evident from Table 3.2-1 that thermionic converters are low-voltage, high-current devices and that to get output voltages of interest one must string converters in series, use a transformer, or both. In addition, because of the high operating temperature and the accompanying gradients, a tradeoff exists between thermodynamic efficiency and device lifetime. Those specific effects that adversely impact device performance and lifetime include the evaporation of cathode material, the reduction of insulator resistance with temperature, stress corrosion, component distortion, and creep.

Potential Method of Employment of Device or Principle in System: Thermionic converters have already been examined with regard to powering conventional microwave generators, and they certainly might be used in the

present context to power auxiliary equipment on a direct solar-to-microwave energy conversion system. However, the objective here was to discover a method whereby a series of converter electrodes might be strung together to create not just a thermal free-electron stream but rather one sufficiently energetic to be utilized in a microwave generator. No such method was uncovered.

Conclusions (Figure 3.2-2): A substantial effort has been invested in the development of thermionic converters for electric power generation in space where either a nuclear reactor or solar radiation might serve as a heat source. Indeed, relative insensitivity to the effects of high-intensity radiation, a high heat-rejection temperature, and the lack of moving parts make thermionic converters well suited to a space environment. However, it does not appear feasible to use them to directly generate an energetic electron beam for use in a microwave generator without first going through the step of producing conventional dc electrical power flowing in a metallic conductor.

References, Section 3.2:

1. G. N. Hatsopoulos and E. P. Gyftopoulos, Thermionic Energy Conversion, MIT Press, Cambridge, Mass., p. 12, 1973
2. G. N. Hatsopoulos and E. P. Gyftopoulos, op. cit., p. 207

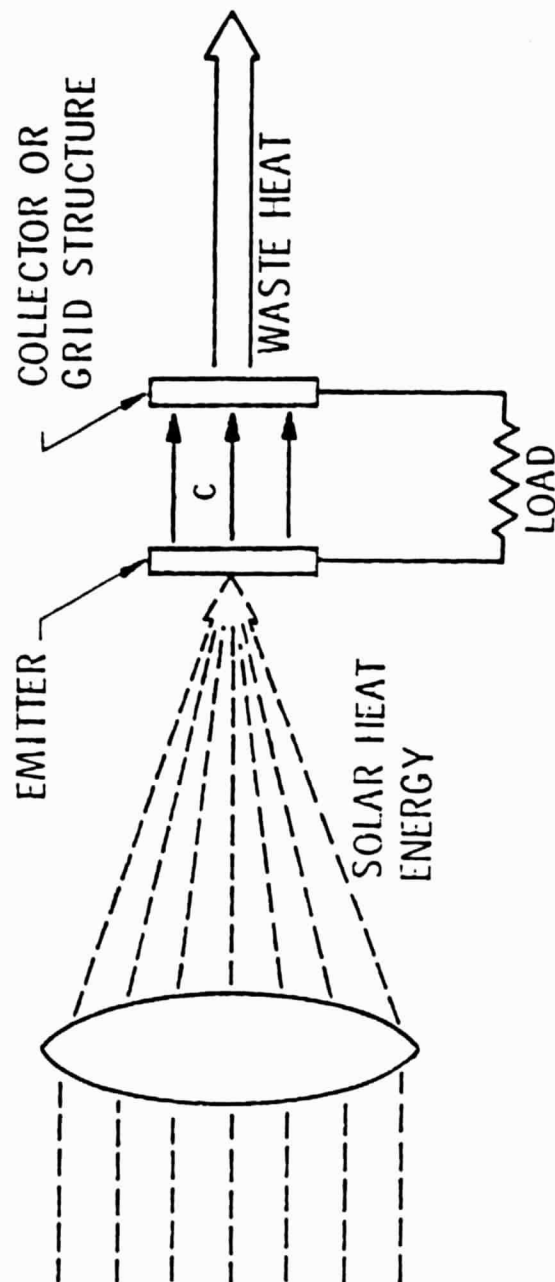


FIGURE 3.2-1. ENERGY TRANSFORMATION TECHNIQUE - THERMIONIC DIODE

TABLE 3.2-1. TYPICAL THERMIONIC DIODE CHARACTERISTICS
(REF. 1)

• EMITTER TEMPERATURE	1,400 TO 2,200 K
• COLLECTOR TEMPERATURE	500 TO 1,200 K
• POWER DENSITY	1 TO 100 W cm ⁻²
• CURRENT DENSITY	5 TO 100 A cm ⁻²
• OUTPUT VOLTAGE	0.3 TO 1.2 V
• POWER OUTPUT	10 TO 500 W
• EFFICIENCY	5 TO 25%

- EFFICIENT OPERATION REQUIRES EMITTER TEMPERATURES OF 1,800 K OR GREATER
- HIGH COLLECTOR TEMPERATURE COMPATIBLE WITH RADIANT HEAT REJECTION
- THERMIONIC DIODES UNAFFECTED BY HIGH RADIATION LEVELS
- LACK OF MOVING PARTS LEADS TO QUIET, RELIABLE OPERATION
- STRINGING THERMIONIC DIODES IN SERIES TO CREATE AN ENERGETIC ELECTRON BEAM DOES NOT APPEAR PRACTICAL.

FIGURE 3.2-2. THERMIONIC DIODE CONCLUSIONS

3.3 DEVICE OR PRINCIPLE: PHOTOELECTRIC EMISSION

Description of Device or Principle: Photoemission of an electron from a solid can occur as a result of the absorption of a photon of energy, $h\nu$, greater than some threshold value (Figure 3.3-1). For metals, this threshold is the work function, ϕ , while for semiconductors and insulators, it is the sum of the band gap energy, E_g , and the electron affinity, E (E is the difference between the vacuum level and the bottom of the conduction band). A distinction can be made between volume and surface photoemission depending on whether the optical absorption is characteristic of the bulk material or merely the few atomic layers below the surface. Because special conditions have to prevail for surface states of the proper type to be present in sufficient density to make significant surface photoemission possible, it is the volume effect that is generally dominant.

Volume photoemission, which can be obtained from any solid for sufficiently energetic photons, can be considered as a three-step process: 1) the absorption of a photon by an electron, 2) the motion of the excited electron to the vacuum-solid interface, and 3) the escape of the electron over the potential barrier at the surface. While the height of the surface barrier bears directly on the threshold for photoemission, the absorption coefficient and the energy loss processes encountered as the excited electron travels through the solid determine the photoelectric yield. The large number of "free" electrons in the conduction band of a metal are responsible for high optical reflectivity and hence low absorption in the visible and near-ultraviolet region of the spectrum. Furthermore, because electron scattering is an effective energy loss mechanism for excited electrons, these same conduction-band electrons severely limit the escape depth of the photoexcited electrons. Consequently, photoemissive yields for metals are very low, less than 10^{-3} per incident photon.

On the other hand, the photoemissive yields of some semiconductors approach their theoretical quantum limit because of the efficiency of the

first two steps of the photoemission process. Semiconductors have much lower reflectivities than metals, while the absorption coefficient for photon energies above the band gap energy, E_G , is often very high, on the order of 10^5 to 10^6 cm^{-1} . Furthermore, the relative lack of conduction band electrons means that energy loss processes other than electron scattering prevail. With regard to this point, a sufficiently energetic electron can excite a valence band electron into the conduction band, thereby forming a secondary electron-hole pair and at the same time losing an amount of energy equal to or greater than the band gap energy. This process is characterized by a relatively short mean-free path (≥ 15 Å) and by a threshold energy, E_{Th} , which is usually several times the band gap energy because of the need to conserve energy and momentum directly. Below the pair production threshold, phonon scattering is the dominant loss mechanism. Phonon scattering is characterized by a relatively long mean-free path (~ 100 Å) and a small energy loss per collision (~ 0.02 eV). Thus photoexcited electrons with energies less than E_{Th} can reach the surface relatively unimpeded and escape depths as great as 250 Å are possible.

Semiconductor photoemitters can be classified according to the relative magnitudes of the band gap energy, E_G , and the electron affinity, E_A . For the most efficient of these photoemitters, E_A is smaller than E_G . Because of the relationship between E_G and the pair production threshold, E_{Th} , a relatively large energy band exists in this case for which photoexcited electrons have a high probability of escaping into the vacuum since the prevailing energy loss mechanism is phonon scattering. Furthermore, it is possible in this case for an electron with an energy above E_{Th} to be left with an energy above E_A after a pair production event and thus also have a high probability of escaping to the vacuum. Relevant information on the more efficient photoemitters, all of which fall into the class described above, is presented in Figure 3.3-2.

Limitations on Device or Principle: Photoemission is primarily a phenomenon of the ultraviolet and visible region of the spectrum and is largely insensitive to the substantial fraction of solar flux occurring in

the near infrared. This point is portrayed in Figure 3.3-2, which displays the response curve of a typical photoemitter along with an approximate solar power spectrum; this data is tabulated in Table 3.3-1.

Additional limitations stem from the chemical properties of the most sensitive photoemissive compounds, all of which contain one or more of the alkali metal elements. Alkali elements react readily with oxygen, water vapor, etc., and thus compounds containing them must be made and maintained in a vacuum. Furthermore, the subject compounds exhibit poor thermal stability and decompose at temperatures in the region of 100 to 200°C. This behavior could severely limit the irradiance levels that a large-scale photoemissive device in space could tolerate.

Potential Method of Employment of Device or Principle in System: The photoelectric effect is a possible source of low energy (≤ 2 eV) that could be used, after acceleration, in a free-electron maser or similar device. Photoemission from solids has the lowest threshold of the several forms of the external photoelectric effect (external refers to electron emission into the vacuum), and several compounds have yields in the 30 to 40% range in their region of best sensitivity. The effect is intrinsic to the subject material and does not require supporting apparatus to make it operative.

Conclusions (Figure 3.3-3): The effect has promise as a source of free electrons, but chemical properties of efficient photoemitting materials present production and operational difficulties. Only low-energy electrons can be produced.

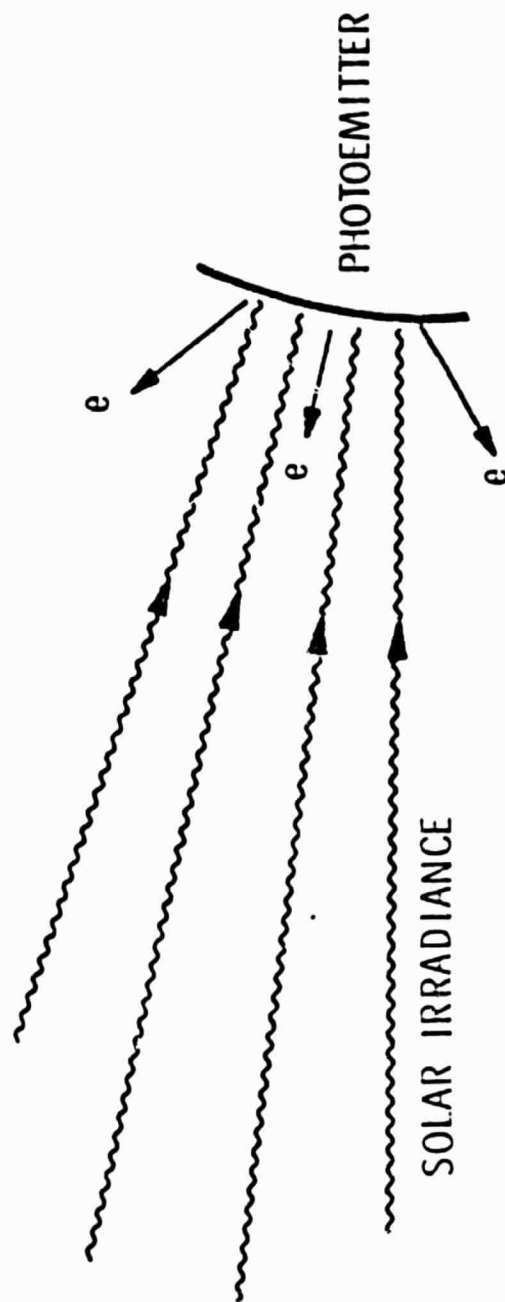


FIGURE 3.3-1. ENERGY TRANSFORMATION TECHNIQUE - PHOTOEMISSION

Data on Efficient Photoemitters

MATERIAL	λ (THRESHOLD)	λ (PEAK)*	Q. E. (max)
K_2CsSb	6600 \AA	4000 \AA	.30
$[Cs]Na_2KSb$	8700	4000	.30
$K_2CsSi(0)$	7800	4000	.35
Na_2KSb	6200	4000	.25

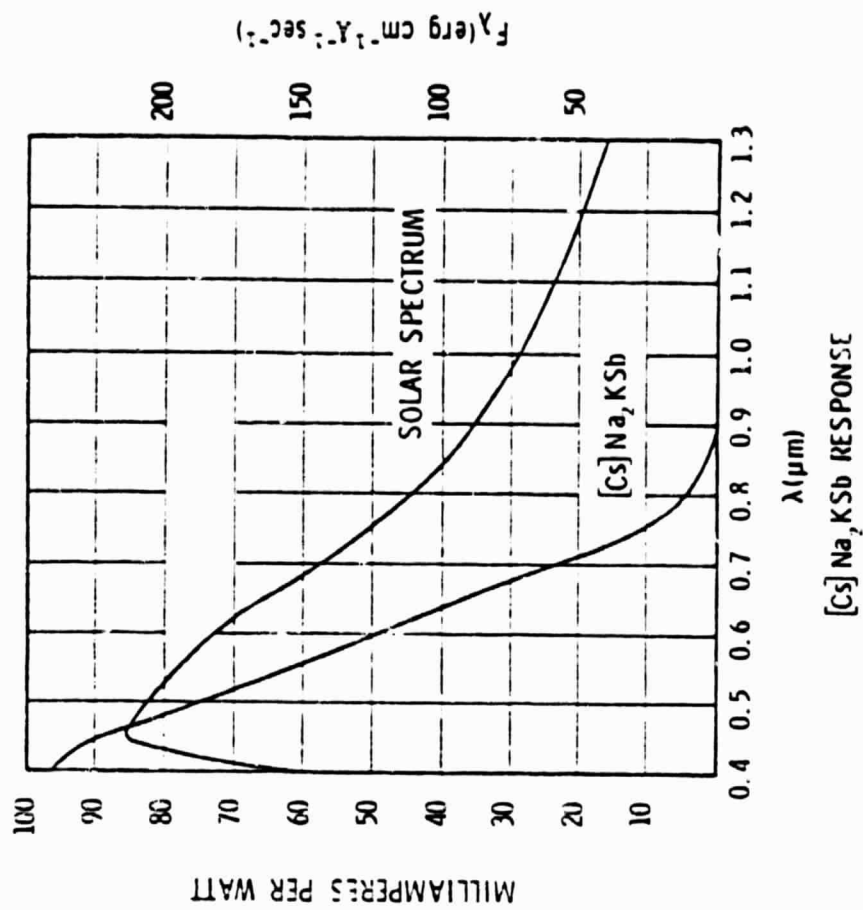


FIGURE 3.3-2. PHOTOELECTRIC RESPONSE

TABLE 3.3-1. CURRENT LIMITED PERFORMANCE FOR (Cs) Na₂ Ksb

<u>POTENTIAL CURRENT</u>		
<u>SPECTRAL REGION</u>	<u>AVAILABLE PHOTONS</u>	<u>EQUIVALENT CURRENT (mA)</u>
ENTIRE	$6.43 \times 10^{17} (\text{cm}^{-2} \text{ sec}^{-1})$	103
ABOVE CUT-OFF	2.2×10^{17}	35
<u>CALCULATED CURRENT</u>		
<ul style="list-style-type: none"> ● ELECTRONS GENERATED: $2.9 \times 10^{16} \text{ cm}^{-2} \text{ sec}^{-1}$ ● CURRENT GENERATED: 4.7 mA 		
<u>ELECTRON GENERATION EFFICIENCY</u>		
<ul style="list-style-type: none"> ● IN BAND OF SENSITIVITY: 13 PERCENT ● RELATIVE TO TOTAL PHOTON FLUX: 4.6 PERCENT 		

- THE COMPATIBILITY OF PHOTOEMISSION WITH THE SOLAR SPECTRUM IS FAIR.
- POTENTIAL PHOTON-TO-ELECTRON CONVERSION EFFICIENCY IN BAND OF SENSITIVITY IS FAIR.
- POTENTIAL PHOTON-TO-ELECTRON CONVERSION EFFICIENCY RELATIVE TO TOTAL PHOTON FLUX IS POOR.
- BEST PHOTOEMITTERS ARE DIFFICULT TO PRODUCE, EXHIBIT POOR THERMAL STABILITY, AND REACT READILY WITH OXYGEN, WATER VAPOR, ETC.

FIGURE 3.3-3. PHOTOELECTRIC EFFECT CONCLUSIONS

3.4 DEVICE OR PRINCIPLE: PHOTOIONIZATION

Description of Device or Principle: Photoionization is the phenomenon that occurs when a photon of sufficient energy is absorbed by a gaseous state atom or molecule resulting in the subsequent ejection of an electron and creation of an electron-ion pair (Figure 3.4-1).

Limitations on Device or Principle: The threshold for photoionization of an element in its ground state is determined by its first ionization potential. The lowest known ionization potentials for both atomic and molecular species are found among the alkali metals, data for which are presented in Figure 3.4-2 (Ref. 1). While photoionization of excited species would occur at a somewhat lower threshold, it is unlikely that a meaningful excited state population would be created either thermally or through resonant absorption within the solar emission spectrum under the conditions of interest here.

Cesium ranks lowest among the individual elements, with a photoionization threshold of 3.87 eV in terms of energy or 3,184 Å in terms of wavelength. This means that only 2% of the solar energy flux is accessible through this phenomenon, or only about 0.6% of the photon flux. The poor compatibility of photoionization with the solar spectrum is depicted in Figure 3.4-2. All other atomic and molecular species have higher thresholds than cesium and thus have lower solar energy conversion efficiencies.

Potential Method of Employment of Device or Principle in System: Photoionization was studied as a source of electrons and as a mechanism for creating a medium that could be used to pump a laser or in which electrons might be accelerated. With cesium used as an example, the photon flux above the 3.87-eV threshold is approximately $4.2 \times 10^{15} \text{ sec}^{-1} \text{ cm}^{-2}$. Assuming 100% conversion efficiency, the maximum available electron current per unit cross sectional area of collector becomes $6.7 \times 10^{-4} \text{ A cm}^{-2}$.

In practice, one cannot utilize the ionization or free electrons as they are generated, and thus the steady-state electron-ion concentrations become of interest. The steady-state concentrations can be estimated by considering photon absorption as an ionization source and electron-ion recombination as an ionization sink. Thus, for an elemental volume a distance z into the medium,

$$\frac{dN_e}{dt} = \frac{dN_i}{dt} = -\frac{dN_0}{dt} = \sigma N_0 N_p(z) - \rho N_i N_e = 0 \quad (1)$$

where

o, e, i - neutral, electron, and ion populations, respectively

σ - photoionization cross section

ρ - recombination coefficient.

$N_p(z)$ is the photon flux per unit area at z and is given by

$$N_p(z) = N_p^0 \exp(-\alpha z) \quad (2)$$

where N_p^0 is the photon flux incident on the vacuum-medium interface at $z = 0$ and the absorption coefficient α is given by αN_0 . Using the relations $N_i = N_e$ and $N_0 = N_T - N_i$ (N_T is the neutral gas concentration in the absence of an ionizing source), one can reconfigure Equation 1 to obtain

$$\rho N_i^2 + \sigma N_i N_p(z) - \sigma N_T N_p(z) = 0$$

which can readily be solved for N_i . Results at $z = 0$ for cesium vapor under a variety of temperature and pressure conditions are presented in Table 3.4-1 for $\sigma = 2 \times 10^{-19} \text{ cm}^2$ (from Figure 3.4-2) and $\rho = 5 \times 10^{-10} \text{ cm}^3$ (Refs. 2 and 3). What the results show is that, because of recombination, a significant fractional ionization is achieved only under extremely low-pressure conditions and that, at pressures above 1 Torr, the relative ion concentration is on the order of one part per million.

Conclusions (Figure 3.4-3): High photoionization thresholds relative to the solar spectral energy distribution limit energy utilization to no more than 2% of that available -- even for cesium, the best case. Furthermore, based on an estimate of the steady-state electron or ion concentration, it is doubtful that a photoionized medium would be of use either for accelerating electrons or for pumping a laser.

References, Section 3.4:

1. G. V. Marr, Photoionization Processes in Gases, Academic Press, New York, p. 108, 1967
2. A. von Engel, Ionized Gases, Oxford University Press, London, p. 163, 1965
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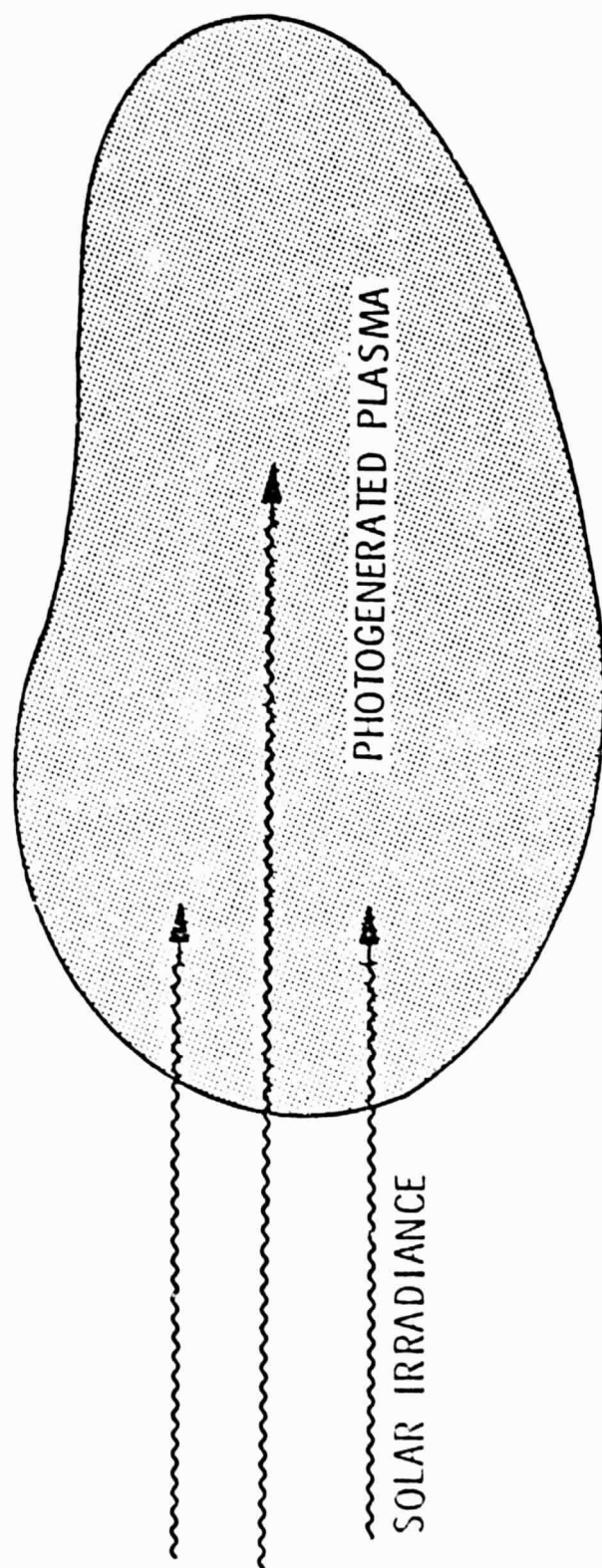


FIGURE 3.4-1. ENERGY TRANSFORMATION TECHNIQUE - PHOTOIONIZATION

DATA FOR ALKALI METAL ELEMENTS (Ref. 1)

ELEMENT	V_i (eV)	λ_i (Å)	σ_t (Mbarn)
Li	5.39	2299	1.8
Na	5.14	2412	0.125
K	4.34	2856	0.007
Rb	4.18	2968	0.10
Cs	3.87	3184	0.20

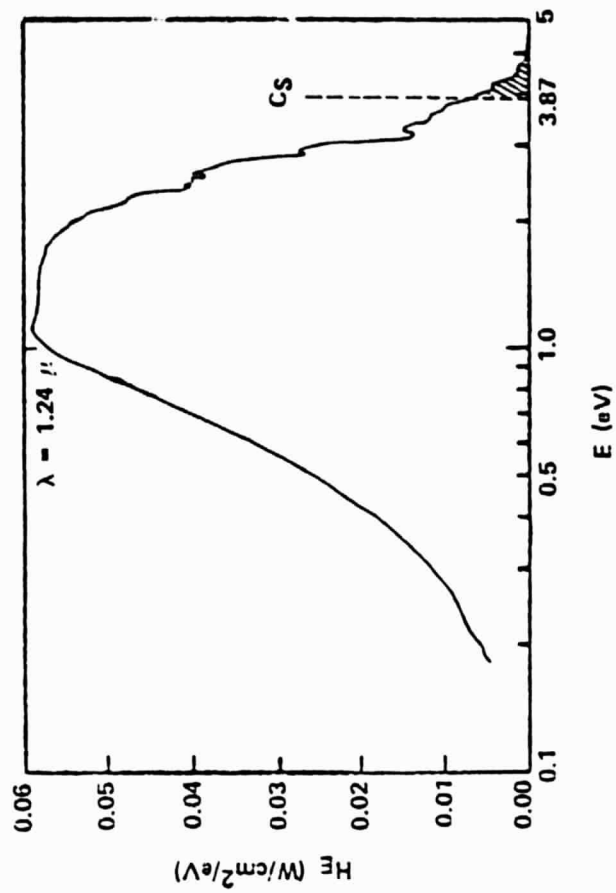


FIGURE 3.4-2. SPECTRAL COMPATIBILITY OF PHOTOIONIZATION PROCESS

TABLE 3.4-1. ESTIMATED CHARGED-PARTICLE DENSITIES IN CESIUM VAPOR

RATE EQUATION

$$\frac{dN_i}{dt} = \text{SOURCE} - \text{LOSS} = 0$$

SOURCE = $\sigma N_{ph} N_0$ WHERE σ WAS TAKEN TO BE $2 \times 10^{-19} \text{ cm}^2$

LOSS = $\rho N_e N_i$ WHERE ρ WAS TAKEN TO BE $5 \times 10^{-10} \text{ cm}^3$

INCIDENT PHOTON COUNT $\approx 4.2 \times 10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$

RESULTS

<u>P(torr)</u>	<u>T(K)</u>	<u>$N_T(\text{cm}^{-3})$</u>	<u>$\alpha(\text{cm}^{-1})$</u>	<u>N_i/N_T</u>
10^{-10}	305	3.2×10^6	6.34×10^{-13}	0.51
10^{-6}	305	3.2×10^{10}	6.34×10^{-9}	0.007
1	552*	1.8×10^{16}	3.5×10^{-3}	9.8×10^{-6}
760	963*	7.6×10^{18}	1.5	4.7×10^{-7}

*VAPOR PRESSURE IN EQUILIBRIUM WITH LIQUID

- PHOTOIONIZATION MAKES POOR USE OF AVAILABLE ENERGY IN SOLAR SPECTRUM.
- RECOMBINATION PREVENTS BUILDUP OF SIGNIFICANT RELATIVE IONIZATION FOR ALL BUT ULTRALOW PRESSURES.
- ELECTRON-ION POPULATION GOES AS $I^{\frac{1}{2}}$ SO BOOSTING SOLAR INTENSITY WOULD LOWER EFFICIENCY.

FIGURE 3.4-3. PHOTOIONIZATION CONCLUSIONS

3.5 DEVICE OR PRINCIPLE: PLASMA GENERATION FROM SOLIDS IN VACUUM

Description of Device or Principle: The interaction of laser radiation with solids in vacuum has been one of the topics of continuing interest since the discovery of the laser. Laser power focused to intensities up to 10^8 W/cm² evaporate materials producing plasmas with energies of a few electron volts. The results are all in good agreement with the classical theories (Ref. 1). The low emitted electron currents (mA) correspond to thermionic emission (Ref. 2) in which the limit is given, not by the Richardson-Dushman (Ref. 3) equation, but by Langmuir's space-charge limit applied to emission current densities (Ref. 4).

The situation changes drastically (and additional phenomena occur) when higher power densities than above are used. Linler (Refs. 5 and 6) used a Q-switched laser to generate plasmas at the surfaces of solids in vacuum (Figure 3.5-1). The power densities used were around 10^9 W/cm². The resulting plasma expanding against the incident laser radiation had velocities of 10^7 cm/sec, indicating energies of 1 keV or more, which is much more than observed at slightly lower laser intensities. The emission of electrons suddenly changes from the classical values of less than 1 A/cm² at 100-kW laser power to 10^3 A/cm² at higher laser power (Refs. 7 and 8). These current densities are far greater than Langmuir's space-charge limitations.

For this situation, the ion energy ϵ_i increases according to the relationship

$$\epsilon_i \sim I^\alpha$$

dependent on the laser intensity, I , where the exponent α is between 1.5 and 2 (Figure 3.5-2). It is, therefore, far greater than a linear function, while gas-dynamic heating of the plasma results in α 's of 0.66 in the best cases (Refs. 9 and 10). The momentum transferred to the irradiated target increases at laser intensities around 10^9 W/cm² as the fourth power (Figure 3.5-3) of the intensity (Refs. 11 and 12).

This highly anomalous behavior of the plasma changes into a much more reasonable mode, amenable to plasma physical models at laser intensities exceeding 10^{11} W/cm². Then the exponent α in the above equation decreases to understandable values around 0.5 to 0.7 (Ref. 13). This highly pronounced anomaly at 10^9 W/cm² (Linlor effect) was obviously little noted, because the reasonable behavior at higher intensities overshadowed the unusual behavior.

Limitations on Device or Principle: There still is no gas-dynamics or plasma-physical explanation for these anomalies, and much study needs to be done for a thorough understanding. The assumption that the fast ions are due to electrostatic acceleration of the thin plasma in the Debye sheath at the surface does not hold, because the number of fast ions exceeds 10^{15} , while a Debye-sheath mechanism can explain only 10^{12} ions or fewer.

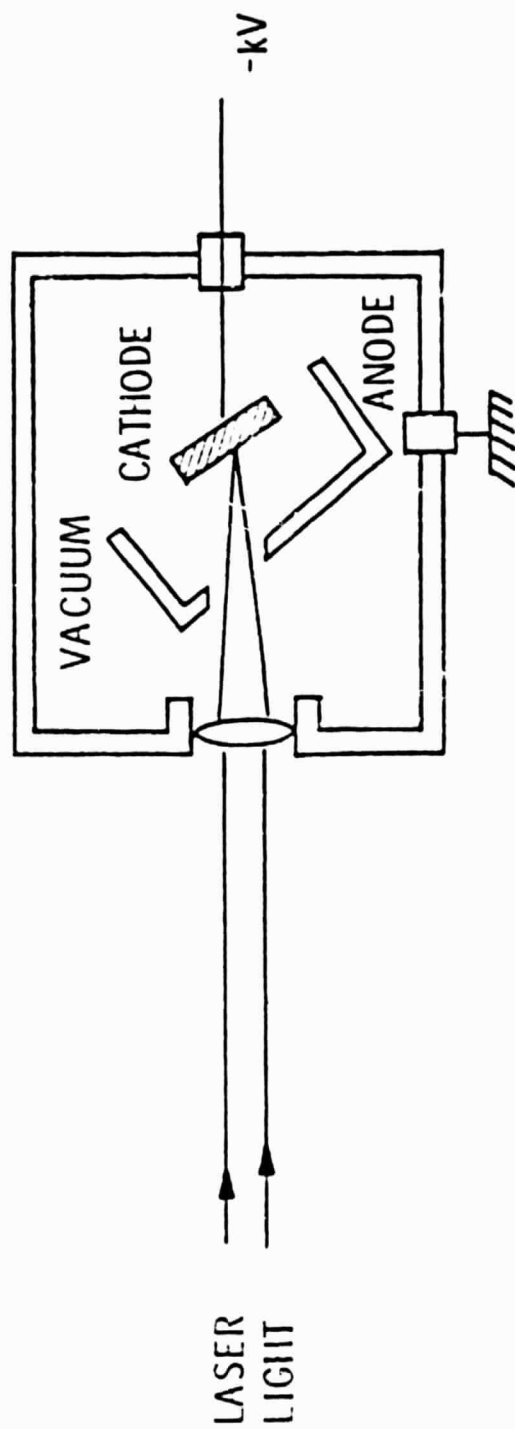
Conclusions (Figure 3.5-4): It can be concluded that there is a potential for generating high-energy electrons from laser-induced plasmas from solids using the Linlor effect. The laser intensity needed for this effect is achievable with several laser devices including Nd:YAG lasers, which have been mentioned as being capable of being solar pumped.

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PLASMA PRODUCTION USING LASER

FIGURE 3.5-1. ENERGY CONVERSION TECHNIQUES - INTENSE ELECTRON EMISSION FROM LASER-PRODUCED PLASMA

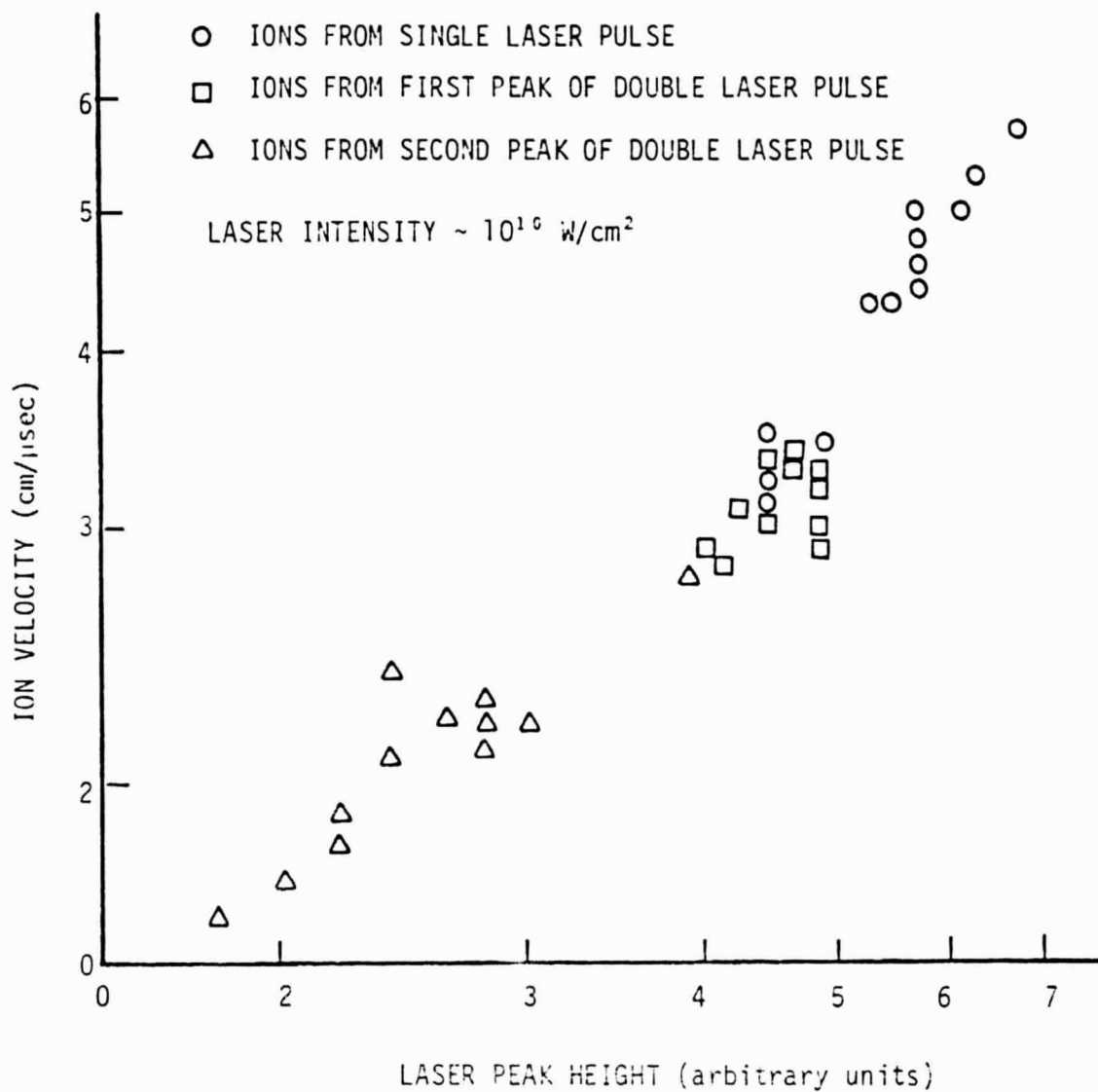


FIGURE 3.5-2. ION VELOCITY PRODUCED BY LASER/SOLID INTERACTION INCREASE RAPIDLY AT INTENSITIES AROUND 10^{16} W/cm²

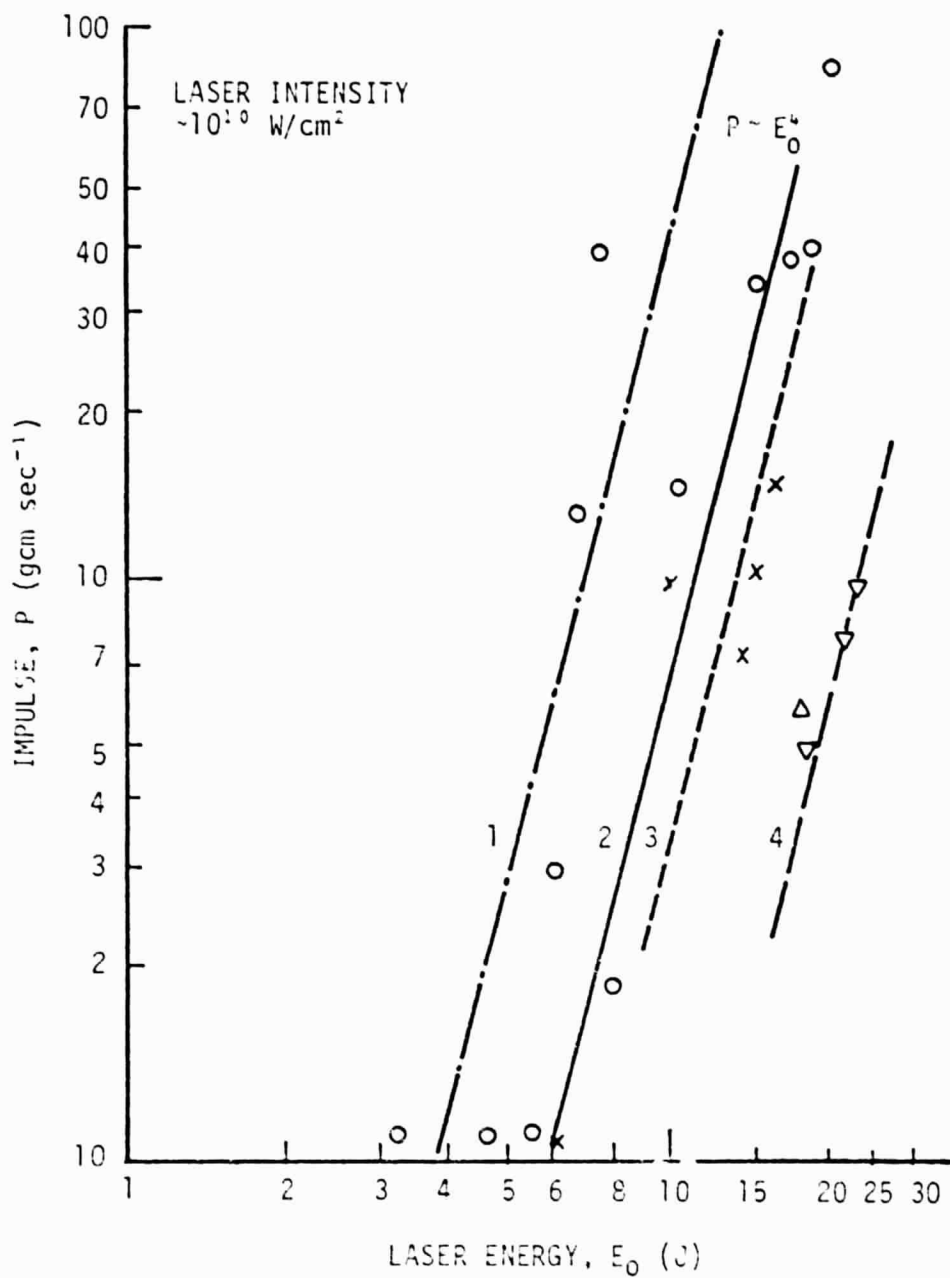


FIGURE 3.5-3. MOMENTUM TRANSFER TO TARGET BY LASER IRRADIATION: AT INTENSITY LEVEL OF 10^{10} W/cm^2

- LABORATORY DEMONSTRATION PERFORMED
- BASIC THEORY NOT DEVELOPED
- POTENTIAL SOURCE OF HIGH-ENERGY PLASMA/ELECTRONS

FIGURE 3.5-4. CONCLUSIONS - LASER/SOLID INTERACTION

3.6 DEVICE OR PRINCIPLE: LANGMUIR WAVE ELECTRON ACCELERATOR

Description of Device or Principle: Various types of instabilities can be generated within a plasma as a result of absorption of energy from an external source (Ref. 1). One such instability, Langmuir oscillations, has been shown to be capable of accelerating electrons directed into the wavefront. One method of production of Langmuir waves in plasma is demonstrated by beaming electromagnetic radiation into the ionosphere. The effect is deduced from the enhancement of the 6,300-Å radiation from atomic oxygen in airglow. Radio-frequency energy is beamed into the ionosphere, producing Langmuir waves that accelerate thermal electrons present in the plasma. These electrons interact with oxygen in the atmosphere and the result is observed as this enhanced airglow (Refs. 2 through 4).

Limitations on Device or Principle: The principle might be applied as a solar-pumped electron accelerator by employing the means shown in Figure 3.6-1. An optically absorbing material is introduced into a localized region of a contained plasma. Solar energy collected in this region is transformed into thermal excitation of the plasma, producing the Langmuir waves. Electrons produced elsewhere or recirculated from the microwave generator are directed into the wave so as to be accelerated.

Highly energetic electrons cannot be produced directly by this process. If the electron energy as it is directed into the wavefront exceeds the potential drop across the wavefront, the electron will pass through the wave. Reference 5 states that electrons with energies of 5 to 10 eV have been produced in the ionosphere with efficiency of conversion of RF energy into electron energy of 0.1%. At an RF power-density level of 1 W/m^2 , the plasma-electromagnetic wave interaction is saturated. Higher-power densities do, however, produce higher fluxes of accelerated electrons.

Conclusions (Figure 3.6-2): The Langmuir wave accelerator can be used to produce electrons of moderate energy with input electrons at thermal energies. There is an inherent limit on the energy produced, the limit

being produced by the depth of the potential well formed in the plasma. To pump the plasma with solar irradiation, optically absorbing elements would have to be introduced at the localized position. To achieve reasonable electron flux densities, the plasma would have to be sufficiently dense so as to require containment.

References, Section 3.6:

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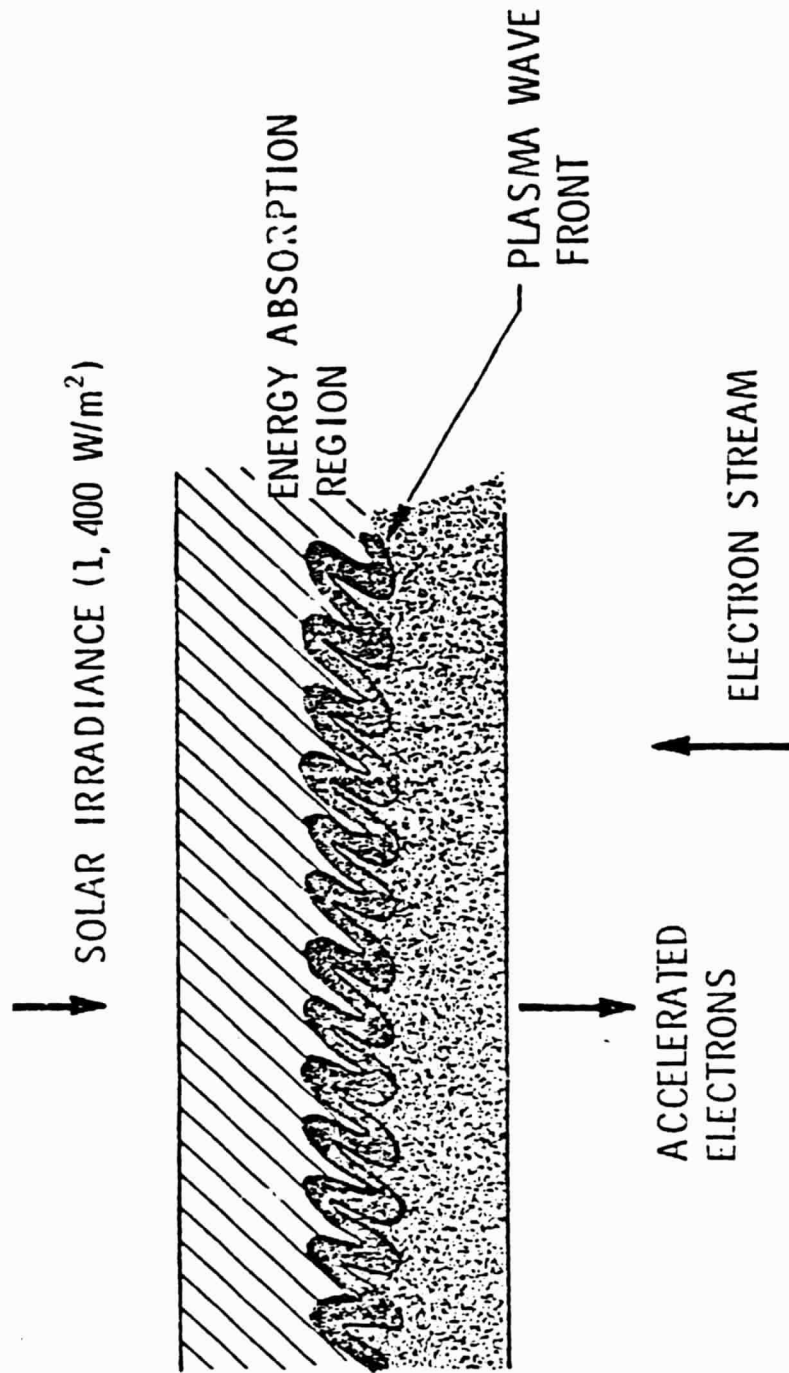


FIGURE 3.6-1. ENERGY TRANSFORMATION TECHNIQUES - LANGMUIR WAVE ELECTRON ACCELERATION

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- 5- TO 10-V ELECTRONS PRODUCED
- SATURATION OF IONOSPHERIC PLASMA AT $100 \mu\text{W}/\text{m}^2$
- UPPER LIMIT OF INPUT ENERGY AT GIVEN DENSITY UNDETERMINED

FIGURE 3.6-2. CONCLUSIONS: LANGMUIR WAVE ACCELERATOR

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3.7 DEVICE OR PRINCIPLE: BETATRON ACCELERATION

Description of Device or Principle: An accelerating electric field is generated by producing a time-varying magnetic flux. Electrons are kept in stable orbits in the betatron system by an appropriate choice of magnetic field as a function of radial distance from the center of the electron orbit. The magnetic field constraining the electrons to an orbit and the acceleration flux are usually produced by the same means (Ref. 1). A schematic of a betatron is shown in Figure 3.7-1.

Limitations on Device or Principle: The betatron system has been used to produce fluxes of electrons at energy levels in the million electron volt range and higher. The device is relatively compact and produces considerable increases in electron energy (Figure 3.7-2). No application was found for production of moderate (kilovolt) energy electrons. Efficiencies and achievable electron densities are unknown.

The betatron represents a transformer in which the orbiting electrons act as one of the windings. This conceptualization can be extended to consider the possibility of a device in which both the primary and secondary transformer windings might be replaced by free electrons in appropriate trajectories.

Conclusions (Figure 3.7-3): The betatron represents a means of accelerating free electrons to high energies. No description of any device was discovered which might be applicable to space power systems. However, the principle is one that warrants additional investigation to determine whether a device concept could be formulated that would have application as an efficient electron accelerator for supplying power.

References, Section 3.7:

1. E. U. Condon and H. Odishaw, ed., Handbook of Physics, McGraw Hill Book Company, Inc., New York, pp. 9-154 to 9-155, 1958

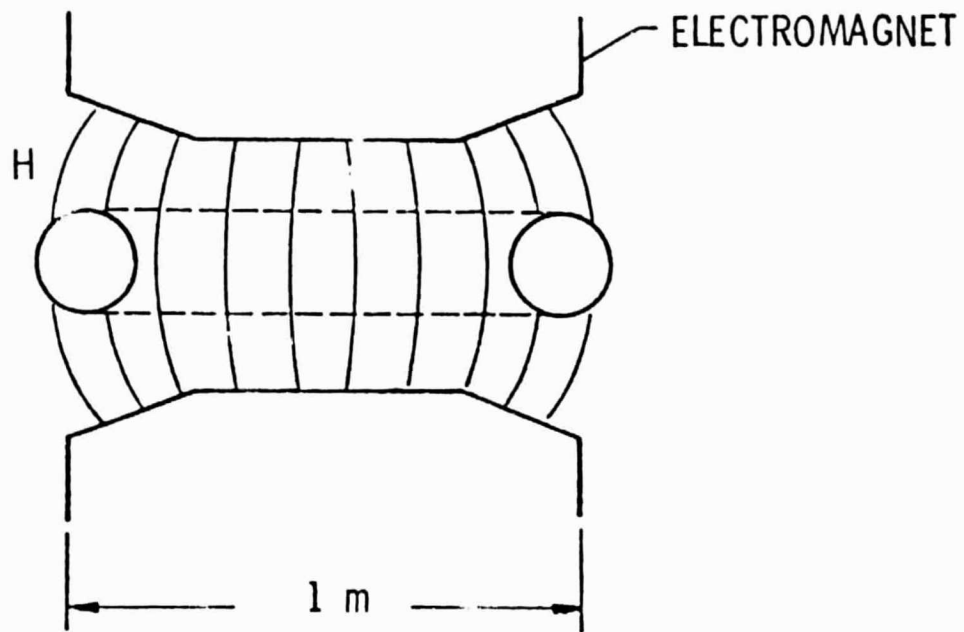


FIGURE 3.7-1. ENERGY CONVERSION DEVICES - BETATRON ACCELERATION

ELECTRIC FIELD PRODUCED PROPORTIONAL TO TIME
RATE OF CHANGE OF MAGNETIC FLUX

FOR $B = 1,000$ gauss

$R = 20$ cm

$\Delta t = 10^{-3}$ sec

FIELD PRODUCED IS

9 V-m^{-1}

FIGURE 3.7-2. BETATRON ACCELERATION

- MODERATE MAXIMUM MAGNETIC FIELD
PRODUCES LARGE ELECTRIC FIELDS
- NO APPLICATION FOUND AT KILOVOLT
ELECTRON ENERGIES
- DEVICE CHARACTERISTICS AS POWER
SOURCE REQUIRE ADDITIONAL STUDY

FIGURE 3.7-3. CONCLUSIONS - BETATRON ACCELERATION

3.8 DEVICE OR PRINCIPLE: MAGNETOHYDRODYNAMIC GENERATOR

Description of Device or Principle: The magnetohydrodynamic generator is a mechanism for converting heat to electricity in a rather direct manner (Ref. 1). Figure 3.8-1 represents such a generator. A plasma is constrained to flow at high velocity through a duct with a magnetic field normal to the flow across the duct. The resultant forces on the electrical charges within the plasma can produce an electric field external to the system which in turn can be used to generate an electrical current or, in the case shown, be used to accelerate free electrons.

Limitation on the Device or Principle: Magnetohydrodynamic generators have been shown to be efficient mechanisms for converting heat energy into electrical energy. Figure 3.8-2 demonstrates this fact, using as an example a system sized according to Figure 3.8-1. The plasma velocities must be high and the plasma reasonably dense in order to achieve the high efficiency noted. A high-strength magnetic field is required. Generally, optimum generation conditions are produced as a result of producing a high temperature in the gas flowing through the duct. The gas also must be "seeded" with an easily ionized material, such as cesium, to produce a close approximation to a plasma.

Conclusions (Figure 3.8-3): The magnetohydrodynamic generator provides a means of production of high-energy free electrons in a manner that is nearer to realization than any other method discussed. Whether such a system would offer advantages over the photovoltaic or solar-thermal systems currently being studied (Ref. 2) is dependent on factors to be discussed in Section 5.

References, Section 3.8:

1. M. A. Kettani and M. F. Hoyaux, Plasma Engineering, John Wiley and Sons, New York, pp. 235-265, 1973
2. C. E. Bloomquist, "A Survey of Satellite Power Stations", PRC Systems Sciences Company, McLean, Virginia, ERDA Contract E(49-18)-2071, September 1976

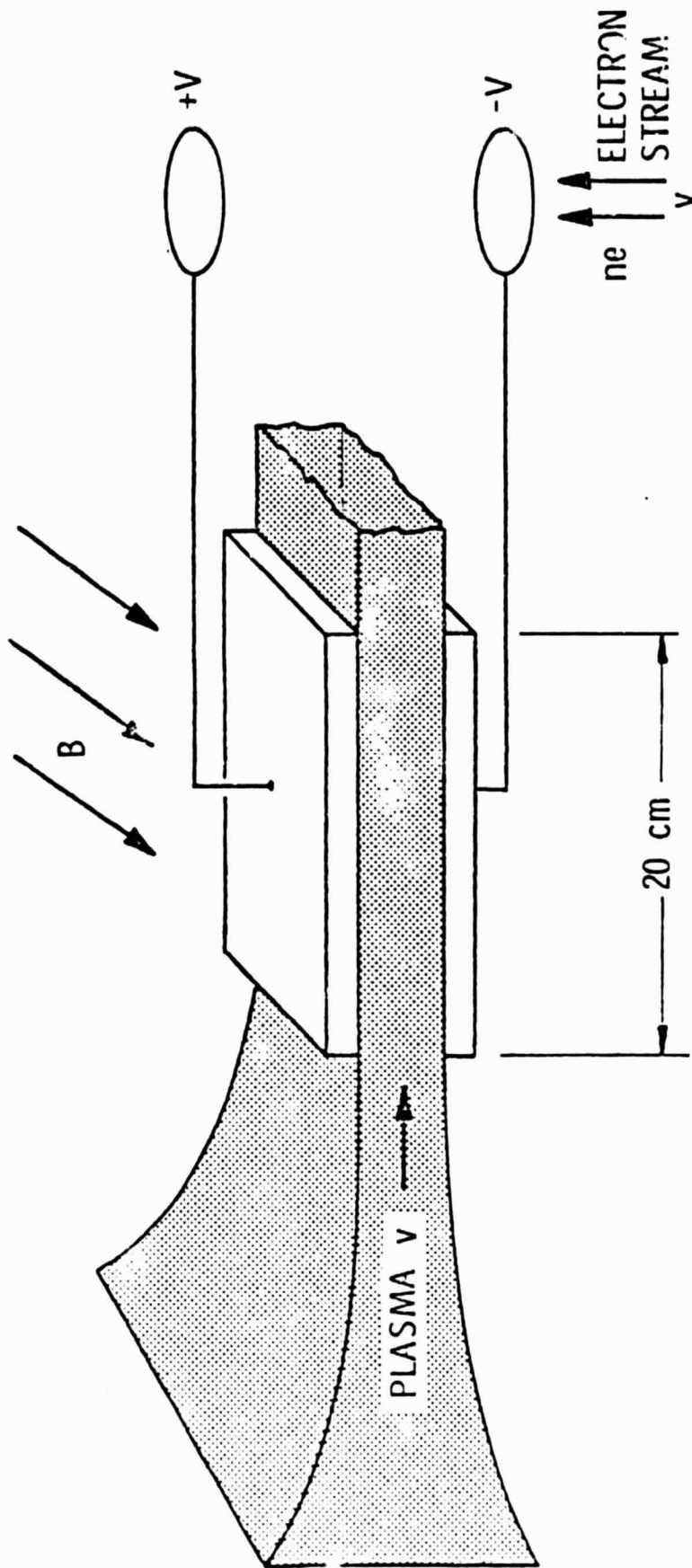


FIGURE 3.8-1. ENERGY CONVERSION TECHNIQUES - MAGNETOHYDRODYNAMIC GENERATOR

POWER DELIVERED: (SYSTEM SHOWN)

$$V = 900 \text{ V}$$

$$B = 10,000 \text{ gauss}$$

$$I = \text{neV} = 6500 \text{ A}$$

$$P = 12 \text{ MW}$$

$$\text{EFFICIENCY} = 50\%$$

$$\text{PLASMA VELOCITY} = 600 \text{ m/sec}$$

$$\text{PLASMA DENSITY} = 10^{-4} \text{ g/cm}^3$$

FIGURE 3.8-2. MAGNETOHYDRODYNAMIC GENERATOR

- HIGHLY EFFICIENT CONVERSION MECHANISM
- USES SOLAR RADIATION TO MAXIMUM EXTENT
- CAN BE USED TO PRODUCE HIGH-VELOCITY-FREE ELECTRONS
- TECHNOLOGY NOT DEVELOPED; REQUIRES COMPLEX SYSTEM; POTENTIALLY MASSIVE STRUCTURES REQUIRED

FIGURE 3.8-3. MAGNETOHYDRODYNAMIC GENERATOR - CONCLUSIONS

4. MICROWAVE GENERATION TECHNIQUES

Potential mechanisms for production of microwave energy were investigated and evaluated. In the course of the evaluation, it was determined that the methods of production could be related to the method by which solar pumping might be accomplished. Generally, microwave radiation was generated through optical mechanisms or through electronic methods (Figure 4-1). The latter techniques are characterized by microwave production through modulation of a free-electron beam.

Results of the evaluations are presented in the same format as was used for the energy conversion techniques in the previous section.

- OPTICAL DEVICES

- ELECTRONIC DEVICES

FIGURE 4-1. MICROWAVE GENERATION TECHNIQUES

4.1 DEVICE OR PRINCIPLE: GENERATION BY RAMAN MIXING

Description of Device or Principle: Using stimulated Raman scattering (SRS) with a high-intensity laser pump, many new intense sources having discrete frequencies can be generated. First successful results were obtained in 1972 (Ref. 1), only after quite important progress in dye laser technology had been made.

Phenomenologically, SRS can be described as a process in which an intense excitation beam amplifies a second beam named the "Stokes beam" with a wave number

$$\sigma_s = \sigma_{ex} - \sigma_{raman}.$$

The energy difference between excitation and Stokes photons is transferred to the medium in which the process takes place. For each Stokes photon created, an excitation photon is annihilated.

Limitations on Device or Principle: The characteristic parameter of this mechanism is the Raman gain, γ . For the process to occur, the excitation and Stokes beams must be perfectly parallel. When the gain is sufficient, a high-power conversion into the Stokes beam becomes possible. The standard test for sufficient amplification is that the quantum efficiency

$$\beta = \gamma I_{ex} \ell$$

be larger than 30, where I_{ex} is the intensity of the excitation beam and ℓ is the interaction length. Parameters connected with the beam medium that may influence the gain are:

- The inverse proportionality of γ to the created wavelength
- Gain proportional to $N/\Delta\nu_R$ for excitation line width smaller than Raman line width, $\Delta\nu_R$, where N is the number of molecules per cubic centimeter.

Potential Method of Employment of Device or Principle in System:

The Raman medium should have the following properties:

- Large gain
- Large vibrational Raman shift
- Weak electric dipole absorption.

The excitation source power needs to be larger than the threshold for the medium such that the quantum efficiency is larger than 30. The Stokes beam divergence has to be kept low. An estimate of the Stokes beam divergence is given by the ratio of the beam diameter to the interaction length necessary to exceed the Raman threshold. Spatial filtering can be used to reduce the divergence.

In stimulated Raman scattering processes, the photon-to-Stokes field conversion efficiency is a maximum of 40%. The advantage of the process is twofold: first, a strong fixed-frequency pump beam can be used to efficiently generate the SRS, and second, to a first approximation, the mixing process efficiency is independent of the intensity of the tunable input beam.

Conclusions: Operating laboratory models exist that generate tunable radiation in the infrared. In one system, powerful infrared radiation continuously tunable between 14,000 and 23,000 cm^{-1} has been obtained with an output power between 5 and 20 MW, depending on wavelength. This year, another system has been developed that operates in the 0.72- to 7.7- μm range and has a peak radiation power of about 10 MW. The input dye laser was pumped with a 2,000-MW ruby (Refs. 2 and 3). Development of a system to generate microwave radiation appears less feasible than for the parametric generator described next. Theoretical efficiencies are also poor.

References, Section 4.1:

1. W. Schmidt and W. Appt, Z. Naturforsch., 27, p. 1373, 1972
2. R. Frey and F. Pradere, Opt. Commun., 12, p. 98, 1974
3. E. D. Minkley, K. W. Will, and F. A. Blum, Laser Focus, 47, p. 21, 1976

4.2 DEVICE OR PRINCIPLE: DIFFERENCE FREQUENCY (PARAMETRIC) GENERATION

Description of Device or Principle: Difference-frequency mixing of two approximate coherent laser sources is performed in a nonlinear material to generate the desired output radiation. Figure 4.2-1 illustrates a possible device for production of microwave radiation using the technique. A "pump" and "signal" beam with wavelengths of X_1 and X_2 are directed into the converter. The converter includes absorption and coupling materials in addition to the nonlinear material. The difference frequency, generally called the "idler" frequency, is produced in the nonlinear material and coupled into a microwave transmission system.

Limitations on Device or Principle: The nonlinear material should be transparent to the signal, the idler, and pump frequencies. This places a limitation on the output frequencies that can be produced based on this property of nonlinear materials available. To obtain maximum conversion of the beam energy into the difference frequency, conditions for phase matching must be met. Phase matching is important because it permits the use of long crystals and affects the efficiency of conversion (Figure 4.2-2). The coherence length for optical-to-microwave conversion is of the order of the wavelength of the microwave output. The device performance is also dependent on the quality of the nonlinear crystal material, which should also have a high damage threshold.

Figure 4.2-3 shows that the output power to be expected is dependent on geometries and material properties that are easily identified. A generalized expression for output power as a function of input and output frequencies points out the most fundamental problem for this technique. Where the difference frequency is far removed from the pump and signal frequencies, the theoretical maximum output power is a small fraction of the input power. As can be seen, the ratio of input power to output power is equal to the ratio of frequencies.

Potential Method of Employment of Device or Principle in System:

Generation of microwave and far-infrared difference frequencies in bulk nonlinear materials has been demonstrated. Millimeter-wave difference frequencies have also been generated by mixing carbon-dioxide laser lines in these nonlinear materials. The highest efficiency demonstrated so far is about 15%, and was obtained by mixing CO₂-laser light in chalcopyrite. The materials that could be used for microwave generation in the 2- to 5-GHz region include gallium arsenide, indium antimonide, indium-bismuth-antimonide, and chalcopyrite.

Conclusions (Figure 4.2-4): This method of conversion of optical frequency energy to microwave energy, while not specifically demonstrated between frequencies of interest, has been demonstrated using infrared radiation to produce 54-GHz radiation. The maximum conversion efficiencies possible on a theoretical basis make the method relatively unattractive.

References, Section 4.2:

1. F. Zernike, Phys. Rev. Letters, 22, p.931, 1959
2. N. Van Tran and C. K. N. Patel, Phys. Rev. Letters, 22, p. 453, 1969
3. D. L. Carter and R. T. Bates, ed., The Physics of Semimetals and Narrow Gap Semiconductors, Pergamon, New York, p. 231, 1971
4. T. Y. Chang, N. Van Tran, and C. K. N. Patel, Appl. Phys. Letters, 13, p. 357, 1968
5. T. J. Bridges and T. Y. Chang, Phys. Rev. Letters, 22, p. 811, 1969
6. A. S. Pine, J. Opt. Soc. Am., 64, p. 1683, 1974

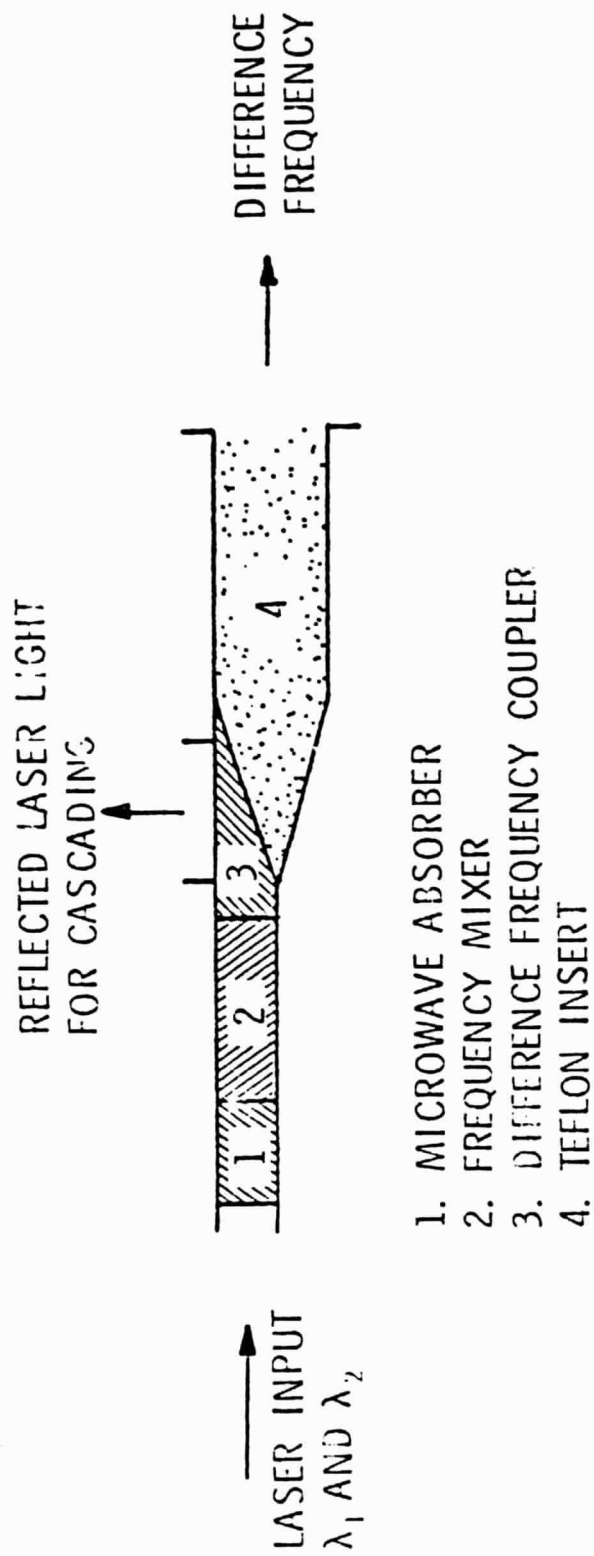


FIGURE 4.2-1. MICROWAVE GENERATION TECHNIQUES - GENERATION BY DIFFERENCE-FREQUENCY MIXING

THEORETICAL COHERENCE LENGTH FOR TE₁₀ MODE

$$l_{coh} = \pi c / \left\{ n_3 \omega_3 - n_2 \omega_2 - \left[K_1 - (\pi c / \omega_1 a)^2 \right]^{1/2} \omega_1 \right\}$$

WHERE

n_2 - REFRACTIVE INDEX AT FREQUENCY ω_2

n_3 - REFRACTIVE INDEX AT FREQUENCY ω_3

K_1 - APPARENT DIELECTRIC CONSTANT OF LOADED WAVEGUIDE

$$\omega_1 = |\omega_2 - \omega_3|$$

$$l_{coh} > 6 \text{ cm for GaAs}$$

FIGURE 4.2-2. COHERENCE LENGTH FOR APPLICATION

THEORETICAL OUTPUT POWER

$$P_{\omega_1} = \frac{32 \pi^2 x^2 \omega_1^2}{3 c^3 n_1 n_2 n_3} \cdot \frac{P_{\omega_2} P_{\omega_3} T^3}{\omega^2} \cdot I$$

WHERE

x - EFFECTIVE SECOND-ORDER NONLINEARITY

ω^2 - CROSS-SECTIONAL AREA OF INCIDENT BEAMS

T - POWER TRANSMISSION COEFFICIENT

I - COHERENCE FACTOR

GENERALIZED POWER RELATIONSHIP

$$\frac{P_{\omega_1}}{\omega_1} = \frac{P_{\omega_2}}{\omega_2} = \frac{(P_{\omega_3})_t}{\omega_3} \left[\frac{P_{\omega_3}}{(P_{\omega_3})_t} - 1 \right]$$

$$\boxed{\frac{P_{\omega_1}}{P_{\omega_2}} = \frac{\omega_1}{\omega_2}}$$

FIGURE 4.2-3. THEORETICAL OUTPUT POWER

- GaAs LABORATORY MODEL GAVE 4 μ W AT 54 GHz FOR 400 W OF CO₂ POWER INPUT
- NOT INVESTIGATED ENOUGH TO POSTULATE DEVICE
- R&D WORK REQUIRED FOR FURTHER DEFINITION

FIGURE 4.2-4. CONCLUSIONS - DIFFERENCE-FREQUENCY MIXING

4.3 DEVICE OR PRINCIPLE: INDIUM ANTIMONIDE CYCLOTRON RESONANCE MASER

Description of Device or Principle: Free electrons can be made to move in close orbits or in spirals when introduced into a magnetic field. Electrons located in conduction bands in semiconductor materials can be made to perform similarly. Such electrons move in a manner that may be treated on the same basis as free-electron motion, except that an effective mass different from the free-electron mass must be used. For a given magnetic field, a resonant frequency exists: the cyclotron frequency. It has been postulated that a semiconductor maser can be produced that will radiate at the cyclotron frequency of the electrons (Figure 4.3-1).

The maser action relies on an electron collision rate that is a rapidly increasing function of velocity to inhibit stimulated absorptions. To obtain amplification, two requirements must be satisfied. The first is that the electron velocity distribution be monoenergetic. The second is that stimulated absorption be inhibited as compared with emission by keeping the photo-generated electron energy just below the optical phonon energy (Figure 4.3-2).

Limitations on Device or Principle: To meet the requirements for monoenergetic electron velocity distribution, the sample needs to be at liquid helium temperature. The photoelectron density that remains monoenergetic is of the order of 10^{12} cm^{-3} . For InSb, this corresponds to a sample thickness of about 10^{-3} cm . The gain for this system will be 2% per pass for the radiation to be amplified (Figure 4.3-3). A magnetic field of up to 15 kG in the direction of the source radiation is needed for cyclotron radiation.

Potential Method of Employment of Device or Principle in System:

The gain can be increased using a multi-pass geometry of the InSb crystal. The electron density of 10^{12} cm^{-3} can be achieved with reasonable pumping power of the order of 1 W/cm^2 . The sample needs to be very thin ($\times 10^{-3} \text{ cm}$) and transparent to the source radiation that is to be amplified. A microwave source can possibly be amplified by pumping the InSb sample with solar radiation meeting the pump criteria.

Conclusions (Figure 4.3-4): This device has not had experimental verification of function as far as we could determine. There might be potential for pumping the device directly with solar radiation to produce the excited electrons needed for operation, although the requirements on electron energy might preclude direct pumping. Large areas of thin films of the semiconductor would be needed, with attendant magnetic fields and cryocooling. Further investigation of the concept should be made to determine whether a device is feasible and to what extent the above operational constraints might be mitigated by its direct conversion feature. Materials transparent to 2- to 5-GHz radiation with the other desired characteristics would have to be identified.

References, Section 4.3:

1. P. A. Wolff, Physics, 1, p. 147, 1964
2. S. Tanaka, K. Mutani, and H. Kubo, J. Phys. Soc. Japan, 17, p. 1800, 1962

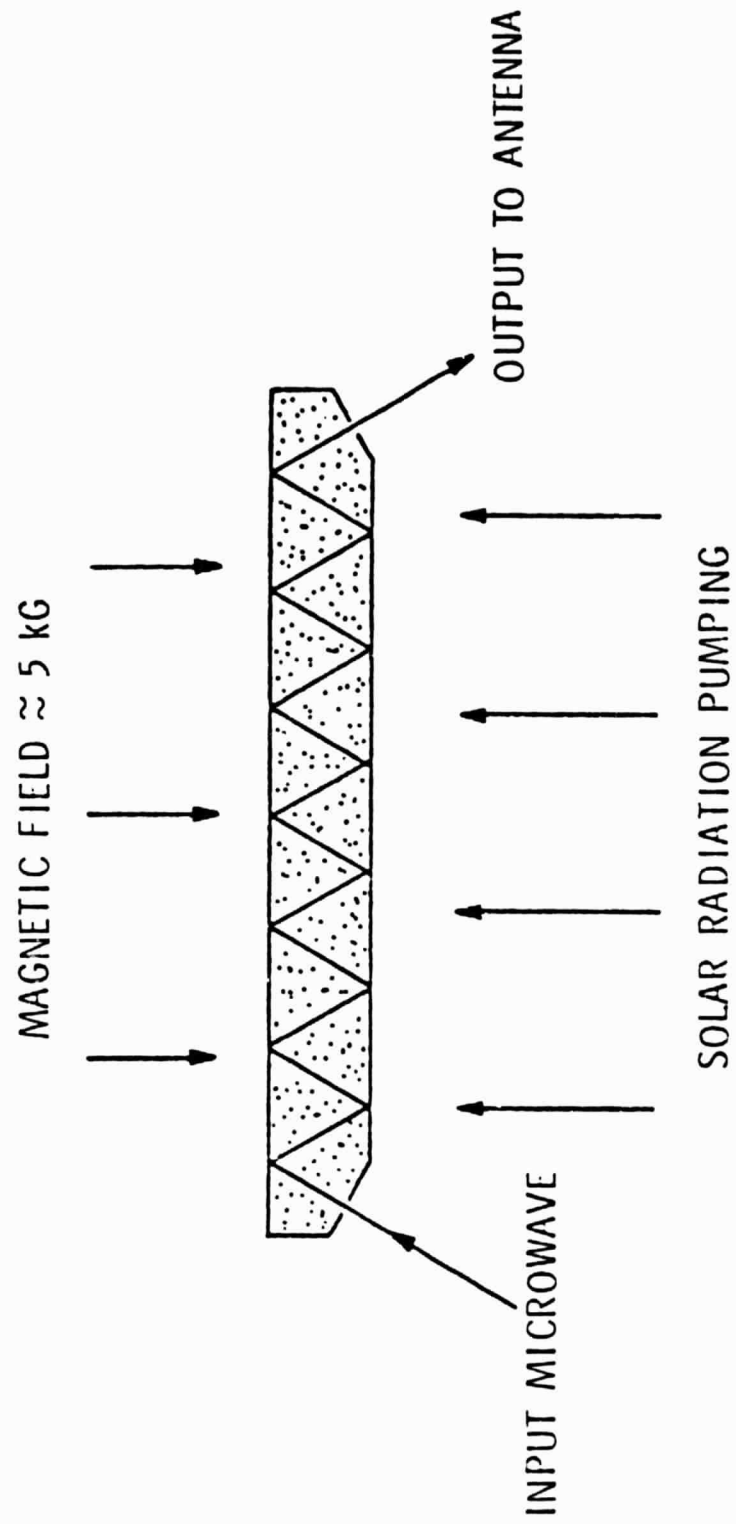


FIGURE 4.3-1. MICROWAVE GENERATION TECHNIQUES - SOLID-STATE CYCLOTRON RESONANCE MASER

- MONOENERGETIC ELECTRON VELOCITY
- INHIBITION OF STIMULATED ABSORPTION
- CONTROLLED PHOTOGENERATION
- NONPARABOLICITY OF CONDUCTION BAND
- VELOCITY-DEPENDENT EFFECTIVE MASS
- ELECTRON COLLISION RATE AN INCREASING FUNCTION OF VELOCITY

FIGURE 4.3-2. CONDITIONS FOR GENERATION

1) THEORETICAL GAIN

$$G = \frac{4 \pi n e^2}{m^*} \left(\frac{\bar{n}}{\gamma_0 c \sqrt{\epsilon}} \right)$$

WHERE

γ_0 - LINE WIDTH OF TRANSITION

ρ - PHOTOELECTRON DENSITY

\bar{n} - AVERAGE LANDAU LEVEL QUANTUM NUMBER

2) GAIN IN INDIUM ANTIMONIDE

SAMPLE SIZE: $1 \times 1 \times 2 \times 10^{-3}$ cm

ρ : 10^{12} cm⁻³

γ_0 : 2×10^{11} sec⁻¹

PUMP POWER: 1 W/cm²

G = 2% PER cm

FIGURE 4.3-3. DEVICE GAIN RELATIONSHIPS

- THIN FILM SAMPLES MAY GIVE THERMAL PROBLEMS
- LARGE AREAS NEEDED
- DEVICE TECHNOLOGY NOT DEVELOPED
- THEORETICAL STUDIES PRIMARILY DONE -- ADDITIONAL THEORETICAL WORK ON APPLICATION OF PHENOMENOLOGY MIGHT BE USEFUL
- SELECTION OF MATERIALS REQUIRED

FIGURE 4.3-4. CONCLUSIONS - SOLID-STATE CYCLOTRON RESONANCE MASER

4.4 DEVICE OR PRINCIPLE: FREE ELECTRON MASER

Description of Device or Principle: The development of centimeter and millimeter wavelength sources at power levels comparable to that obtained at lower frequencies from conventional klystrons and TWT is of great interest to a number of important applications. This interest has resulted in development of a device which might have application as alternatives to klystrons and amplitrons.

This device is based on interaction of electromagnetic waves with electrons oscillating in macroscopic static fields -- that is, on stimulated emission. The electrons here behave such that they may be considered classical oscillators. Therefore, these devices also may be called classical electron masers (CEM). Another name for this type of device is cyclotron resonance maser (CRM). A specific example may be considered of a relativistic electron beam passing through a transverse periodic magnetic field. Amplification of the stimulated radiation in the direction of the electron beam is achieved. The gain is ascribed to bunching of the electron distribution in the presence of the field. Treated on a quantum mechanical basis, the electrons in this state are placed in distinct energy states and emit coherent radiation as they transit from one state to another through the action of the magnetic field.

Generally speaking, there are many ways to provide macroscopic oscillatory motion of electrons. For this purpose, one may use either homogeneous fields, fields inhomogeneous in the direction transverse to the electron drift, or periodic static fields. Accordingly, the various types of CEMs are rather numerous. Among them, the CEMs with homogeneous static fields seem to be most attractive because of their simplicity and because of the possibility to confine intense electron streams with uniform parameters in large volumes.

In a static magnetic field, electrons move along a spiral path at the cyclotron frequency. In order to provide coherent emission of an electromagnetic wave by the electrons, it would seem enough to impart to them this cyclotron energy. The influence of an electromagnetic wave on an electron beam gives rise to an alternating current that can lead to stimulated emission and absorption. For energy generation, stimulated

emission has to exceed absorption. This can be achieved through the relativistic dependence of the cyclotron frequency, or inhomogeneity of the alternating electromagnetic field.

The basic components of a practical CRM are shown in Figure 4.4-1. The basic needs are a source of electrons, magnetic field, cavity, and output waveguide. The length of such a system can vary between 0.2 to 3.0 m, depending on the technique used, power generated, and the generated frequency. In general, the cavity size is independent of the frequency of the stimulated emission.

Limitations on Device or Principle: The efficiency of the present device is limited by the fraction of the electrons' energy which can be converted to radiation in a single pass through the interaction region (Figure 4.4-2). The gain falls at short wavelengths and a higher electron current is necessary for operation in the millimeter-wave region of the optical spectrum. Figure 4.4-3 is a plot of efficiencies and powers attained at two different wavelengths as a function of electron current. Devices have been operated at high efficiency at harmonics of the cyclotron frequency -- which decreases the magnetic field strength requirements.

Potential Method of Employment of Device or Principle in System:

The frequency of the masing output is dependent on the electron energy, the magnetic field strength, and the period of the magnet. Thus the system is capable of operating at high power with tailored frequency. The device might be operated in closed cycle by reaccelerating and recirculating the electron beam through the interaction region. This would also increase the efficiency of energy conversion compared with a single-pass system. For mildly relativistic electrons, the stimulated radiation is distributed over wide angular cones and the intensity emitted in the backward direction is almost the same as that in the forward direction. On the other hand, the emission from highly relativistic electrons is beamed in the forward direction into a narrow cone.

Conclusions: This device appears to have potential for space use. Some problem areas that need additional investigation are shown in Figure 4.4-4. This device is an alternative to the klystron or

amplitron system; its potential has not yet been fully assessed. It lacks a narrow frequency output as presently configured, which is a serious problem, but it conceivably has potential as a single-element, higher-power device than the alternatives.

References, Section 4.4:

1. A. V. Gaponov, M. I. Petelin, and V. K. Yulpatov, Radio Phys. and Quantum Electronics, 10, p. 794, 1967
2. J. L. Hirshfield and J. M. Wachtel, Phys. Rev. Letters, 12, p. 533, 1964
3. Y. Carmel and J. A. Nation, J. Appl. Phys., 44, p. 5268, 1973
4. M. Friedman, D. A. Hammer, W. M. Manheimer, and P. Sprangle, Phys. Rev. Letters, 31, p. 752, 1973
5. V. L. Granatstein, M. Herndon, R. K. Parker, and P. Sprangle, IEEE J., QE-10, p. 651, 1974

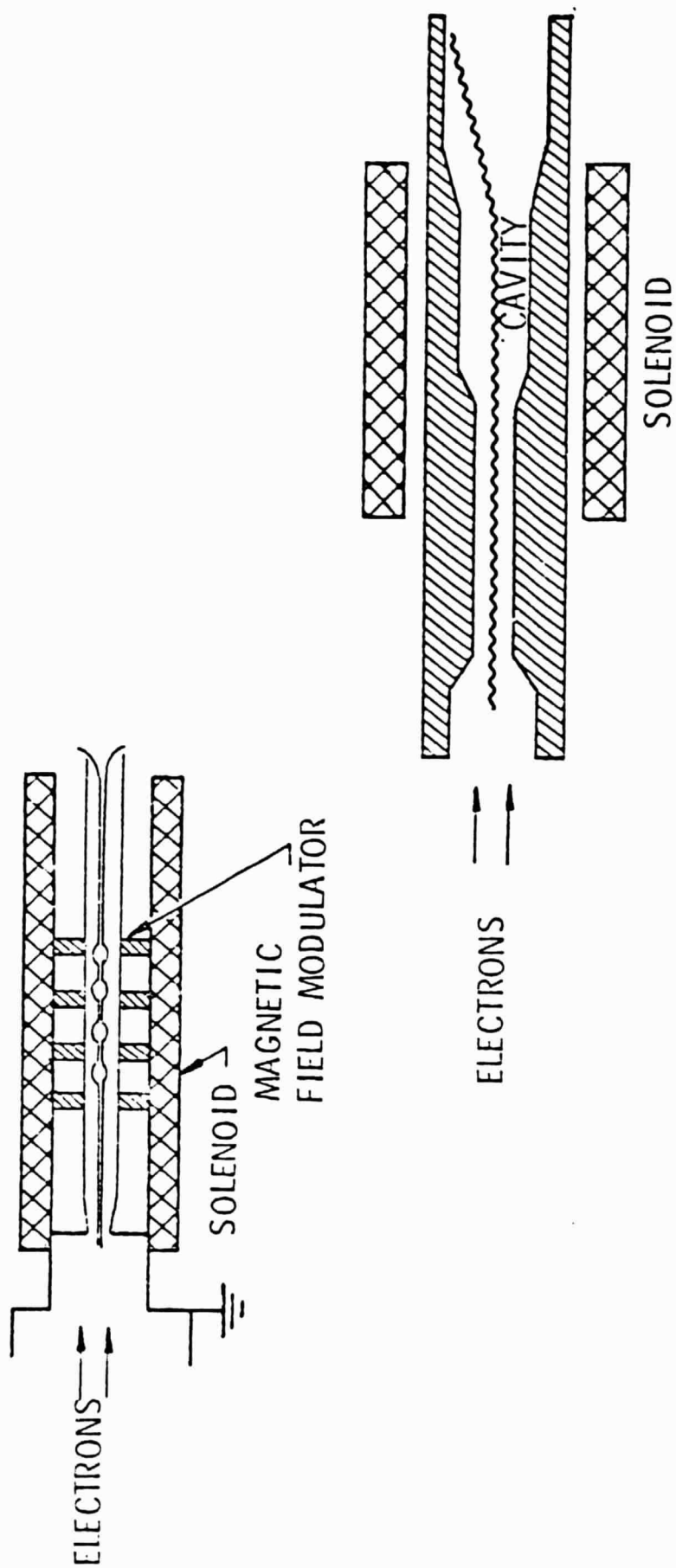


FIGURE 4.4-1. MICROWAVE GENERATION TECHNIQUES - FREE ELECTRON MASER

- ELECTRON-OPTICS SYSTEM
- BEAM CURRENT
- CAVITY RESONATOR LENGTH
- CAVITY Q-FACTOR
- OUTPUT WAVEGUIDE COUPLING

FIGURE 4.4-2. EFFICIENCY-DETERMINING PARAMETERS

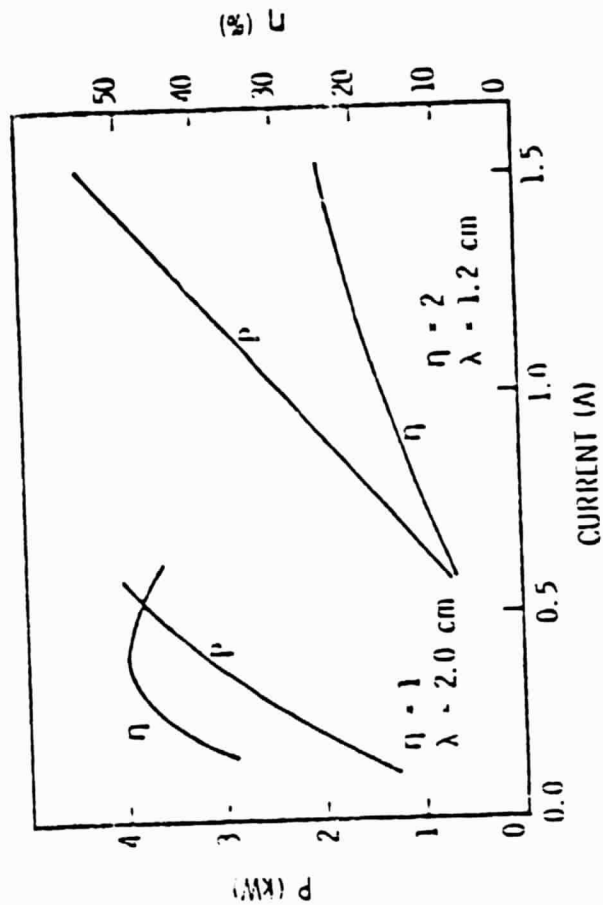
OUTPUT EFFICIENCY:

$$\eta = (1 - Q/Q_{om}) \eta_e L$$

$\eta_e L$ - FRACTION OF ENERGY TRANSFERRED BY THE ELECTRONS TO THE RF FIELD

Q - RESONANT CAVITY Q-FACTOR

Q_{om} - OHMIC Q-FACTOR



POWER AND EFFICIENCY AS FUNCTIONS OF ELECTRON CURRENT

FIGURE 4.4-3. PRACTICAL ATTAINABLE EFFICIENCIES

- GENERATION OF TUBULAR STREAM OF ELECTRONS WITH HELICAL TRAJECTORIES
- REDUCING VELOCITY DISPERSION OF THE PRODUCED ELECTRON BEAM
- IMPROVING THE AXIAL SYMMETRY OF THE ELECTRODYNAMIC SYSTEM
- SMOOTHING OF THE CAVITY PROFILE

FIGURE 4.4-4. EFFICIENCY-IMPROVING METHODS

5. SYSTEM CONCEPTS

Based on the results of the investigation of fundamental processes and devices that might be used for conversion of solar energy to inputs to a microwave generation subsystem and the subsequent radiation of the microwave output from that subsystem, preferred system concepts were formulated (Figure 5-1). The same nomenclature may be applied to classes of system concepts as was applied to device/phenomenology descriptions: optical and electronic. The optical systems are characterized by processes that entail conversion of the solar radiation to microwave radiation through interactions involving electromagnetic radiation. The electronic systems generally involve processes in which charged particles are produced as a part of the conversion sequences. It is to be noted that for neither of these systems has a concept been evolved that is not dependent, in addition to the electronic and optical functions, on intermediate stages involving thermal, mechanical, or other processes.

• DEVICE APPLICATION

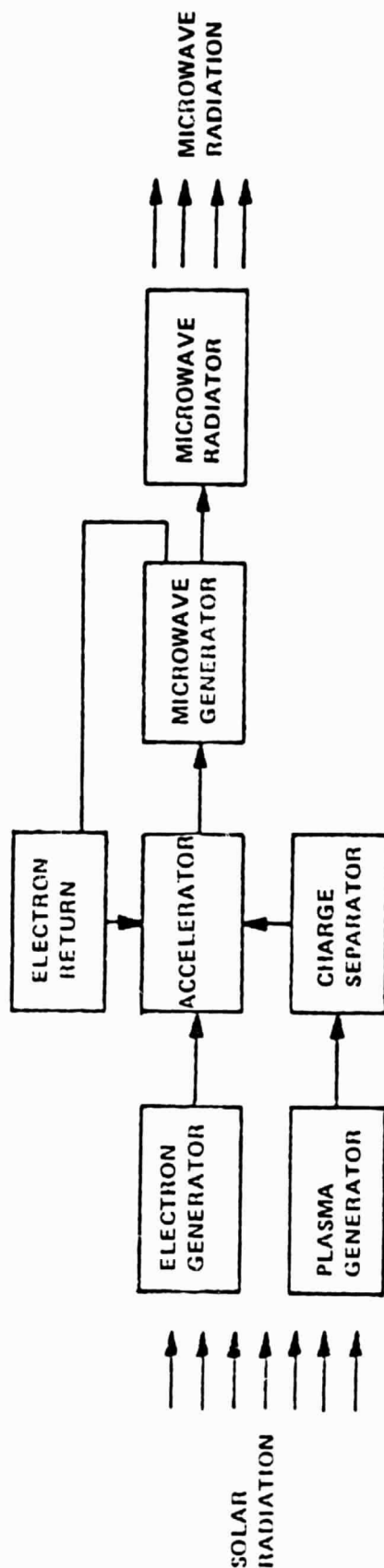
• PREFERRED SYSTEMS

FIGURE 5-1. SYSTEMS CONCEPTS

Figure 5-2 illustrates most of the basic steps involved in the optical and electronic systems. These steps have been formulated by synthesizing the requirements of each device or process concept presented in the last section into generalized system functions. From the functional relationships shown in this figure, conclusions may be reached as to which concepts might be pursued. The viability of concepts developed here may be compared with the baseline photovoltaic systems.

For the electronic systems concepts, the microwave generation scheme using electron beams requires use of either the klystron or amplatron in a fashion similar to the baseline systems or an electron

ELECTRONIC SYSTEMS



OPTICAL SYSTEMS

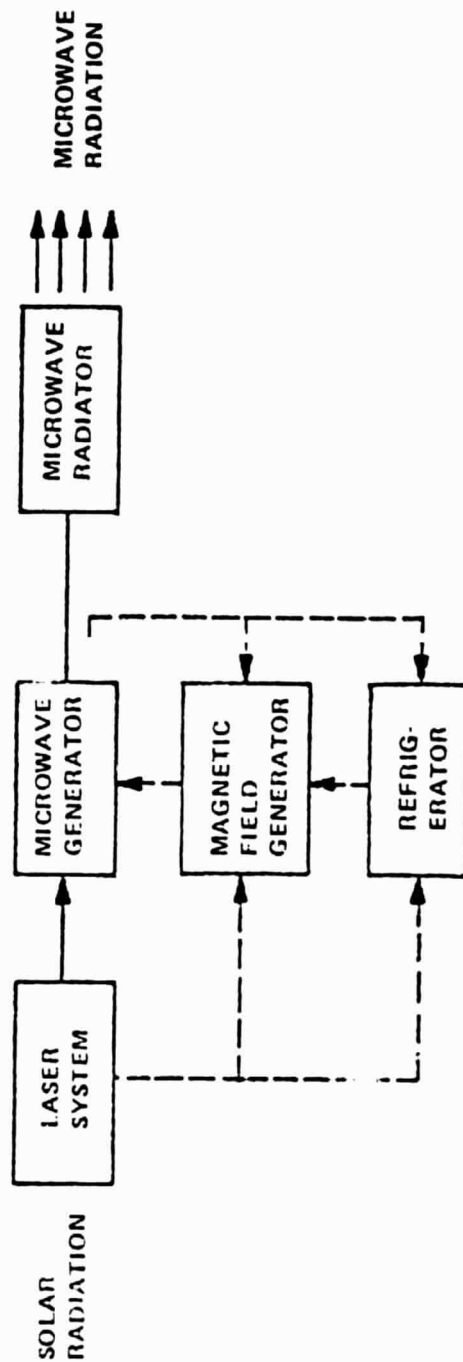


FIGURE 5-2. SYSTEM CONCEPTS

maser (a gyrotron, for instance). The latter device is not as fully developed as the former devices and its current uses are aimed at millimeter-wave production. Its operating characteristics related to physical constraints, bandwidth, and coupling are sufficiently different to attract interest to a more complete study of its possible application to the power satellite.

The electronic system concepts differ from the baseline concepts most markedly in that for the power distribution system free electrons are postulated to be generated and used as carriers rather than the baseline concept of flowing electrical currents through conductors. The problems with employing free electrons in the system are manifold. The most basic problem and one that must be addressed as being basic to the electronic system operation is that of producing electrons energetic enough to be used in the microwave generation devices.

The optical systems virtually all employ a laser as the first mechanism in the conversion process. This fact severely limits the utility of these systems, since if a laser output is produced, there is some evidence that this energy can be efficiently transmitted to the Earth's surface directly. In addition, these systems perform conversions such that maximum theoretical efficiencies achievable are related to the ratio of input to output frequency; this limits efficiencies of the optical systems to approximately 10^{-6} . If optical pumping could be made achievable directly with solar energy, then there might be some reason to reconsider optical systems; therefore, some research activity is suggested in the next section.

The conceptualization of a power satellite employing either of these system concepts is constrained to look something like that shown in Figure 5-3. This representation is close to those produced for the baseline system. The primary features include:

- The collector system is required to include an area equal to or greater than the baseline system.

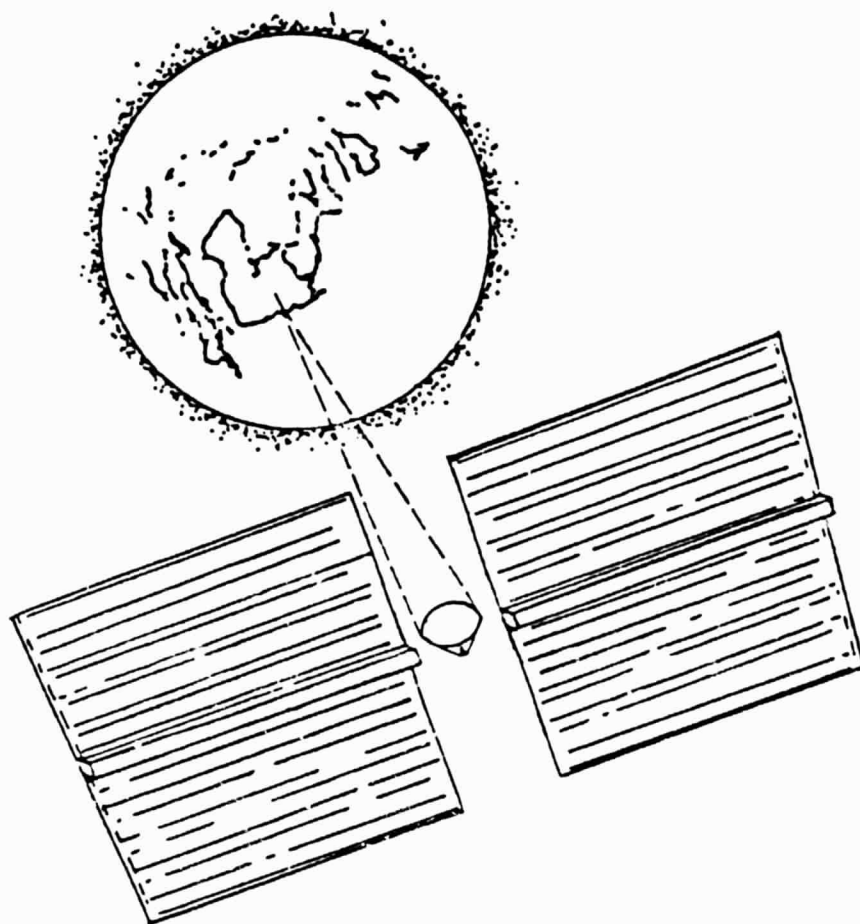


FIGURE 5-3. ELECTRONIC CONVERSION SYSTEM

- The microwave generation and transmission system must be of the same general size as the baseline system's.
- It is possible that the rotary joint transmitting power could be eliminated.

The collector area is determined by collection efficiency and output power desired. None of the concepts and processes investigated appear to hold promise for materially improving collector performance.

The microwave generation and transmission system is sized to produce a desired radiation pattern on the ground from a coherent source. While other constraints might change the size from the baseline concept, the results of this investigation did not affect it. All of the devices and generation mechanisms investigated would require coupling into a radiator system.

In either the optical or electronic systems that might use devices or techniques discussed in this report, the possibility exists for deleting the requirement for a rotary joint for power conduction to the microwave system. Either an optical link or an electron stream would be used instead -- with directional receivers. The impact of this alternative on the system design requires additional study of the orbital parameters, receiver mechanical pointing systems, and the dynamics of the system components.

6. TECHNOLOGY DEVELOPMENT PLAN

Selection of technologies suggested for additional development was made on the basis of device and fundamental principle evaluation and on system concepts as shown in Figure 6-1.

- DEVICE-RELATED DEVELOPMENT
- SYSTEMS DEVELOPMENT

FIGURE 6-1. TECHNOLOGY DEVELOPMENT ACTIVITIES

Several devices or phenomenologies appear to have potential for accomplishing a portion of the energy transformation sequence. No system concept that can be formulated from the basic data presented here can be stated to be a viable alternative to baseline systems currently under investigation by NASA. Certain of the processes and ideas for system functions might be worthwhile pursuing as alternatives which upon further development could be of interest. For this reason, ideas for further development activity are broken down into categories associated with devices or selected aspects of systems rather than for the system concepts as a whole.

Devices knowledge of which is at such a level that they exhibit potential characteristics compatible with incorporation in a power conversion system include:

- Solar-pumped lasers
- Parametric generators
- Solid-state cyclotron resonance masers
- Free-electron masers.

Phenomenologies that are at that level include:

- Photoemission
- Laser-solid interactions
- Free-electron transformers
- Free-electron operating systems.

For the first stage of the conversion process, the production of free electrons or the production of coherent optical energy is required. Figure 6-2 lists development activities of interest for photoemitters and solar-pumped lasers. Development of space-stable high-efficiency photoemitters would provide capability for production of free electrons with a mechanism analogous to photovoltaics in the solid state. Ideally, photoemitters could be designed into a passive network with no active cooling elements required. The reasoning behind development of solar-pumped lasers is to provide a component in an optical system for conversion of solar radiation into microwave radiation. In addition, solar-pumped lasers do offer potential for transmission of the coherent radiation directly to the ground. This latter use is beyond the scope of the current investigation.

Figure 6-3 lists the key activities necessary to the demonstration of the potential of a parametric generator for power production. Figure 6-4 relates the technology development to demonstrate the use of a solid-state cyclotron resonance maser to microwave generation. These two devices have the potential for most directly producing microwave energy from solar irradiation, but theoretically attainable efficiencies are so low that they do not represent preferred elements.

The free-electron maser is a microwave generation device with characteristics differing from the klystron and amplatron proposed for use in the baseline. These characteristics, discussed before, may make this device useful for power production in the system. Before additional extensive theoretical analyses and experimental development are done, projections as to its usefulness cannot be made. Without direction for research and development for power production in the 2- to 5-GHz frequency range, it is doubtful whether progress will be made for this application. Figure 6-5 gives a list of activities that could be performed to further define the potential of this device.

The most conceptually attractive of the systems that were postulated in this study is that in which the power conduction processes are carried out through transfer of free electrons from one element to

PHOTOEMISSION

- EXPLORE IMPACT OF SPACE ENVIRONMENT ON PHOTOEMITTER MATERIALS
- DEVELOP METHODS FOR LARGE SCALE PRODUCTION OF PHOTOEMITTING FILMS IN SPACE.

SOLAR PUMPED LASERS

- DEMONSTRATE AND CHARACTERIZE DIFFERENCE FREQUENCY GENERATION WITH SOLAR PUMPED Nd:YAG LASER
 - ▲ MODE SELECTION
 - ▲ FREQUENCY STABILIZATION
- SEARCH FOR AND DEVELOP SOLAR EXCITABLE GAS LASERS.

FIGURE 6-2. TECHNOLOGY DEVELOPMENT

- ANALYZE OPTICAL AND MICROWAVE PROPERTIES OF NONLINEAR MATERIALS IN THE FREQUENCY REGION OF INTEREST
- STUDY PHASE MATCHING
- PREDICT MAGNETIC FIELD EFFECTS ON PHASE MATCHING AND POWER GENERATION
- DEVELOP PROTOTYPE DEVICE.

FIGURE 6-3. TECHNOLOGY DEVELOPMENT - GENERATION BY DIFFERENCE FREQUENCY MIXING

- STUDY MATERIALS TO DEVELOP HIGH EFFICIENCY
 - ▲ PHOTOCONDUCTIVITY
 - ▲ DOPING EFFECTS
 - ▲ INCREASING ELECTRON DENSITY WITHOUT DISTURBING MONOENERGETIC VELOCITY DISTRIBUTION
 - ▲ REDUCING THE STIMULATED EMISSION LINE-WIDTH
- ANALYZE THERMAL DISSIPATION OF THE DEVICE MATERIAL.
- DEVELOP PROTOTYPE PRACTICAL DEVICE.

FIGURE 6-4. TECHNOLOGY DEVELOPMENT - SOLID-STATE
CYCLOTRON RESONANCE MASER

- DEVELOP ELECTRON BEAM SHAPING AND SEPARATION TECHNIQUES
- DEVELOP SYSTEM WITH MINIMUM MAGNET WEIGHT
- DEVELOP NARROWER BANDWIDTH DEVICES
- PERFORM ANALYSES TO DETERMINE DEVICE CHARACTERISTICS AS FUNCTION OF OUTPUT POWER
- COMPARE GYROTRON SYSTEM TO KLYSTRON OR AMPLITRON SYSTEM.

FIGURE 6-5. TECHNOLOGY DEVELOPMENT -
FREE-ELECTRON MASER

another. This concept differs from the baseline system up to the point of microwave power production. Devices for microwave power production on such a system could be klystrons, amplitrons, or free-electron masers. The free electrons are postulated to be used in these devices rather than electrons generated from a cathode. Electrons could be recirculated rather than collected at an anode. To produce such a system, technology development according to Figure 6-6 must be carried out. The basic problem with a free-electron system is that the electrons cannot be produced with a sufficient energy to be useful in any microwave generation device investigated (with one possible exception - the laser/solid interaction). A means of accelerating the electrons to the kilovolt-energy level must be developed. To be useful, the accelerator must produce the accelerating field without using a direct exciting potential. The reason for this is that such a direct potential would have to be produced using a photovoltaic system or a solar thermal system considered in the baseline studies. An approach of that type abrogates the reasons for a free-electron system. High-energy electrons can be produced through laser-solid interaction and by transformer actions. The laser-solid interaction is interesting but requires the intermediate step of production of a coherent optical beam. Once a laser providing power is in the system, using beamed laser energy to the ground looks like a more promising alternative.

A more definitive technology development plan is not warranted on the basis of the information gathered during this investigation. No device or system concept is either promising enough or developed fully enough to lay out a development program. The study has pointed out, we believe, that additional basic investigations are warranted to explore unconventional approaches to space solar power systems that could employ properties of the environment at orbital altitudes as a portion of the system functioning.

- DEVELOP THEORY OF MECHANISM OF PLASMA GENERATION BY LASER/
SOLID INTERACTION IN ANOMALOUS POWER REGION ($\sim 10^9$ W)
- PERFORM THEORETICAL AND EXPERIMENTAL DEVELOPMENT OF "FREE
ELECTRON TRANSFORMERS"
- ANALYZE ELECTRON OPTICS SYSTEMS FOR CIRCULATION OF FREE
ELECTRONS
- CONCEPTUALIZE FREE ELECTRON SOLAR OPTICAL TO MICROWAVE
POWER CONVERSION/TRANSMISSION SYSTEM

FIGURE 6-6. TECHNOLOGY DEVELOPMENT - PREFERRED CONCEPTS

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